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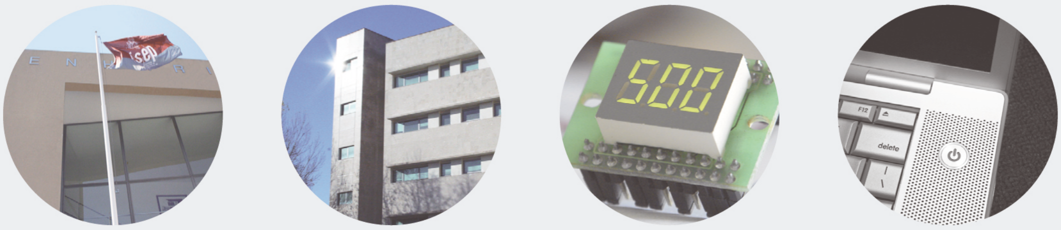
MESTRADO EM ENGENHARIA ELECTROTÉCNICA E DE COMPUTADORES




# Wireless sensor network for collecting environmental data and controlling several parameters in the perimeter of a vegetable farm

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# Abstract

This project was developed under the framework of the Tese/ Dissertação (TEDI) Curricular Unit, of the second year of the Masters in Electronical Engineering and Computers, Telecommunications specialization.

The topic is the development of a system that collects and processes data by the means of a wireless sensor network utilizing the ZigBee standard, in the frame of a vegetable farm. The farm facility includes a variety of buildings that perform different functions related to the farm and also the area which contains the cultivated terrain itself.

The system uses different devices that work together in order to process the data collected from the sensors and also allows the user the ability to control and alter specific parameters related to agriculture, security and automation such as humidity of the soil, security of the perimeter, illumination systems and heating systems for the plantations and the buildings.

Accompanying the network is a program equipped with a Graphical User Interface (GUI) that processes the collected data from the sensors, issues the commands to the devices and provides statistical reports by keeping a history of the values of the parameters observed and the decisions taken.

The research activity includes the practical execution of a pilot network containing two data collecting nodes, a coordinator, a server and the associated software developed throughout the project.

## Keywords

wireless sensor network; environmental characteristics control; farm monitoring; plant characteristic study

# Acknowledgements

First of all, I want to express my gratitude to my supervisor Professor Cecília Reis for the amazing oportunity to finish my studies abroad and for the understanding and all the help and advice given.

I wish to thank Professor Ion Marghescu for proposing the interesting topic and challenge and for allowing me to use the university facilities to develop the project. I also wish to thank Professor Alexandru Martian for his time and help to carry on the radiofrequency tests.

Lastly, I wish to thank my parents for all the assistance and support given, most of the times by long distance, not only during the development of the project but also during my academic and personal journey.

# Contents

# List of Figures

# List of Tables

# Acronyms

| | |
|---|---|
| ADC | Analog-to-Digital Converter |
| AF | Application Framework |
| APP | Application |
| APS | Application Support Sublayer |
| BLE | Bluetooth Low Energy |
| BPSK | Binary Phase-Shift Keying |
| CSMA-CA | Carrier Senser Multiple Access with Collision Avoidance |
| DC | Direct Current |
| DIO | Digital Input/Output |
| DSSS | Direct Sequence Spread Spectrum |
| EVM | Error Vector Magnitude |
| FAQ | Frequently Asked Questions |
| FFD | Full Function Devices |
| GTS | Guaranteed Time Slot |
| GUI | Graphical User Interface |
| IDE | Integrated Development Environment |
| IEEE | Institute of Electrical and Electronic Engineers |
| I/O | Input/ Output |
| ISM | Industrial, Scientific, Medical |
| LR-WPAN | Low-Rate Wireless Personal Area Network |
| MAC | Media Access Control |
| NTC | Negative Temperature Coefficient |
| NWK | Network |
| OQPSK | Offset Quadrature Phase-Shift Keying |
| OS | Operative System |
| PHY | Physical |
| PTC | Positive Temperature Coefficient |
| RFD | Reduced Function Devices |
| SMT | Surface Mounted |
| THT | Through-hole |
| WSN | Wireless Sensor Network |
| WWW | World Wide Web |
| ZC | ZigBee Coordinator |

| | |
|---|---|
| ZDO | ZigBee Device Object |
| ZED | ZigBee End Device |
| ZR | ZigBee Router |

# Chapter 1

# Introduction

The present work was developed during Erasmus+ mobility, from September 2018 until July 2019 in Universitatea Politehnica din Bucuresti, under the supervision of Professor Ion Marghescu. The remaining work was developed in Portugal, in order to obtain the graduation level of Master in Electronics and Computers, under the supervision of Professor Cecília Reis from Instituto Superior de Engenharia do Porto.

## 1.1 Contextualization

Agriculture is one of the oldest and largest fields of work that has been practiced for thousands of years, providing food to communities and with the increase in the world population, the demand for food has also increased, causing the resources necessary to augment substantially, which raises concerns about the future and the sustainability of the current methods and their environmental impact in the short and long term on the planet. By farming, entire communities can be fed, as such, agriculture has a major role at a global scale by providing a variety of aliments. Increasing the efficiency of the process leads to higher yields with reduced expenses and lower ecological impact, meaning it has potential to contribute even more to the increase of the food stock worldwide. [1]

The most important element to agriculture is water and even though some farmers still depend on rainfalls, much of the big scale agriculture is fueled by water withdrawn from freshwater sources such as rivers and lakes, which make for 70 % of the all the water withdrawn globally and approximately 40 % of the world's food is cultivated in artificially withdrawn water. [2] For this reason, efficient production methods are not only needed for companies to increase profit and decrease costs, but they are also a necessity to reduce the heavy impact created by the thousands of agricultural enterprises and farms around the world. Such impact can bring great social, financial and ecological implications, caused by the excessive withdrawal of water from natural sources like rivers and lakes, leading to the dryout of these water sources that are of great importance for the life of local communities and wild life.

Therefore, automation and precise control of the workings of the farms and facilities can greatly improve the functioning of the agriculture complexes, reducing the amount of wasted water and excessive electricity consumption by keeping the essential atmospheric conditions in the intervals that provide the best nutrients for the plants and at the same time provide a bigger yield from the crop, maximizing both the amount of food obtained and the profits while at the same time reducing the overall ecological impact.

Taking into account modern technology and connectivity, it's possible to build such a system, with low cost materials that have the advantage of being wireless and easily integrated in the complex itself. This simplifies the installation and turns it into a more affordable solution by reducing the amount of materials and costly infrastructure modifications needed, which in turn makes it more accessible for lower budget farms that might not have the capital to automate their businesses.

## 1.2 Objectives

The objective of this research activity is to design and develop an adaptable wireless sensor network (WSN) for studying, maintaining and controlling the perimeter of an hypothetical vegetable farm. In order to have a more precise planning, the project will be divided in the following tasks:

1. Background study of farm facilities and the technologies available for the project.

2. Development of a program with a Graphical User Interface (GUI) that allows the user not only to analyse the functioning of the farm complex with real-time parameters displayed but also to manage the farm by controlling the thresholds for different actions and parameters and study the evolution of the farm by observing statistical reports and graphics created with values from the database that contains an history of the values and the decisions taken by the user.

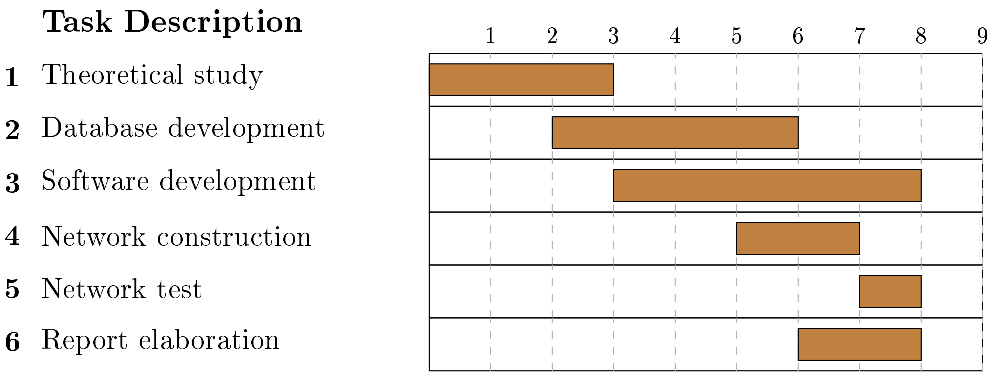
3. Preparing a server that will collect, process the obtained data and run the network management program.

4. Construction of the wireless sensor network itself, which will include xBee Modules to transmit the information to a coordinator and from the coordinator to the server as well as Arduino modules to control the functioning of the communication nodes and to prepare the data collected from the sensors for transmission.

5. Discussion of the practicality, usability and costs of the obtained network as well as a study of the advantages and disadvantages in real world applications.

## 1.3 Chronological Planning

Taking into consideration the division of the project in the section before, an estimated chronological planning can be made in months:




## 1.4 Report Structure

The present report is divided in five main chapters with each covering a different part of the work developed, along with an appendix and bibliography.

In Chapter 1, the project is introduced with a brief contextualization, along with the objectives to be accomplished by the end of the project and the project's timeline and structure as well.

Chapter 2 includes a theoretical analysis of the various subjects and technologies involved in this project. Such theoretical topics are agricultural facilities, wireless sensor networks and ZigBee networks with real world applications.

The practical development of the project is covered in Chapter 3 which includes all the steps performed for the duration of this research activity.

In Chapter 4, the final results obtained are presented along with a posterior discussion and analysis.

Chapter 5 consists in the conclusions that were obtained during the project as well as the final result with a brief overview of the entire process.

Finally, there is an Appendix that complements the report along the several chapters with images and procedures regarding the topic at hand.

# Chapter 2

# Theoretical Framework

## 2.1 Vegetables

In order to develop the project, a brief study on agricultural facilities and their structure along with the types of vegetables that are produced is necessary.

There are many species of vegetables, however, only around fifty vegetable species have a wider share in the global agriculture producing markets. In order to organize and document the different species, several types of classification of vegetables exist:

- Botanical
- Hardiness (temperature)
- Plant part used
- Culture and production methods
- Life cycle

Botanical classification relies on the biological caracteristics of the vegetables, grouping them in increasingly specific groups, such as family, genera, species, sub-species, etc. While this classification is the most organized and precise, it's not the most appropriate for farmers and enterprises since vegetables in the same family can have completely different production methods as can be seen in the following list of commonly produced vegetables classified by their botanical family:

- Fabaceae: peas, beans, lentils.
- Solanaceae: tomatoes, eggplants, peppers, potatoes.
- Brassicaceae: cauliflower, cabbage, brussels sprouts, broccoli.

- Allium: onions, garlic, leek, shallot, chives.
- Apiaceae: carrots.
- Asteraceae: lettuce.
- Cucurbit: melon, cantaloupe, cucumber, calabash, squash, and pumpkin.
- Gramineae: sweet corn.

Classification according to hardiness or temperature divides the vegetables in Winter season and Summer season vegetables. Classifying vegetables by the plant parts used divides the leaves, stems, fruits, flowers, roots, bulbs, etc. Vegetables can also be classified based on their life cycle, which can be annual, biennial or perennial. While these classification methods are certainly more helpful to growers than solely classifying the vegetables based on botanical family, they still group vegetables with very different methods of cultivation together.

Therefore, dividing the vegetables according to the culture method is the most useful and practical for companies and farmers, since the vegetable groups share the similar methods, they can be grouped together in the agricultural facility, increasing space and energy efficiency as well as allowing more specific growing conditions. [3]

## 2.2 Vegetable Farms

The vegetables are grown in farms and these farms have certain qualities that dictate how the vegetable is grown and the conditions it has access to. Vegetable farms can range from a small scale growery to a full scale agricultural complex and can be divided in outdoor farms or indoor farms.

Outdoor farms are the most common, where the vegetables are out in the open or inside a greenhouse. In the case of outdoor farms, the vegetables are more exposed to the elements, thus the crop and the culture method is more reliant on the environment and it's characteristics.

Indoor farms are farms inside buildings in which artificial lighting is normally used as a light source in order to compensate for the lack of sunlight, with modern light technology, specific light spectrums can be achieved. Plants and vegetables grown indoors can be maintained in the ideal environmental grow conditions for the total duration of the grow, which may lead to increased yield from the crops. Indoor farming while more precise and perfected than outdoor growing needs a substantially higher investment than outdoor growing which includes the facility, lighting, water and energy expenses.

## 2.3 Control Parameters

Vegetables are plant-based forms of life, as such they need certain conditions to grow and prosper. In case these conditions are not met, the vegetable may not grow to it's fullest potential, become stressed and might be of inferior quality, thus making the complete agricultural process less efficient.

Some of these conditions can be altered and measured, and these measurements make the control parameters that form the basis of the controlling functionalities of this project. These are the values that will be read by the sensors and analyzed further in the software which will then know when and which actuators to activate in order to keep the conditions in the optimal interval that makes the vegetables thrive.

### 2.3.1 Atmospheric

#### Carbon Dioxide

Carbon Dioxide or $CO_2$, is a gas vital to plant growth and is absorbed by the plant's leaves in order to perform photosynthesis. Photosynthesis is a chemical process where plants use the $CO_2$ combined with water drawn through the roots and the light they receive in order to manufacture food for growth and respiration. The gas can be measured in parts per million or *ppm*, which is the concentration of the gas and it's quantity can be controlled. Supplementing plants with $CO_2$ brings beneficial results stimulating the plant's photosynthesis process and growth, especially on legumes and vegetables which are more responsive to the increases in $CO_2$. [4]

#### Humidity

Humidity is the concentration of water vapour present in the air is also a source of water for the plants. Three types of humidity measurement exist, specific, absolute and relative.

Specific humidity is a parameter that does not depend on atmospheric temperature or pressure, but with masses. It is the ratio between water vapour mass and mass of dry air. [5]

Absolute humidity relates to the water vapour content present in a cubic meter or kilogram of air, it is commonly expressed in $g/m^3$ or $g/kg$, respectively.

Relative humidity is expressed as a percentage and is a mathemathical function that represents the ratio between the absolute humidity and the water vapour amount that would exist at saturation for a given temperature. Seen as it depends on pressure and temperature it can also be an indicator of the surrounding environment. [6]

#### Light

Light is essential to the photosynthesis process, plants use energy from the light, therefore require a certain minimum amount of light that varies depending on the species, otherwise they don't grow as strong due to lack of nutrients.

Illumination is measured in lux units, or $lx$, which is the amount of light that reaches a certain surface. Lumens, or $lm$, is used to measure the amount of light that a light source is capable of emitting. [7]

#### Oxygen

Oxygen or $O_2$, is produced during the photosynthesis process, however when the plant is not illuminated it consumes $O_2$ and it is necessary for the respiration process of the plant, where it is absorbed by the roots of the plant. Quantities in of oxygen in the air are measurable in parts per million, or *ppm*, and the gas amount can be easily increased in the grow space through the use of oxygen tanks.

#### Temperature

Some plants survive in cold weathers while other plants survive in warmer weathers depending on their hardiness. Each plant has an ideal temperature range in which they are at the healthiest and provide the best crop, however, should a plant be in a space outside it's temperature range, there is the possibility that the plant might freeze with the cold or be burned by the heat.

#### Wind

Air contains $CO_2$ and $O_2$ therefore wind or fresh air circulation is benefitial to the plants because it carries these elements that over time are depleted. Wind helps plants breathe and contributes to strengthening the plants when they are younger.

On the other hand, too much air circulation may cause root stress, structural damage to the plants and leads to increased water loss due to evaporation.

### 2.3.2 Soil & Water

#### Nutrients

Apart from the main necessities like carbon dioxide, water and oxygen plants need a variety of nutrients that are important, and in some cases, vital to growth. These nutrients can be divided in macronutrients and micronutrients, acording to their importance. Plants get some of these nutrients from the soil, meaning they can be fed when watering the plants, added as fertilizers or already present in the soil substrate. [8]

#### pH

The pondus Hydrogenii level or pH level of a solution ranges from 0 to 14 and indicates if it is acidic or alkaline, in case it it is inferior to 7 or superior to 7, respectively. If the pH of the solution is 7, it is a neutral solution.

The pH level influences the absorbability of chemical elements by the plant, with an acid solution being easier to absorb and an alkaline solution being harder to absorb. A pH level too low or too high can have adverse results, hindering growth, causing specific conditions related to the excess of nutrients due to excessive absorption or lack of nutrients due to reduced absorption, respectively. [9]

pH levels are measured with pH indicators or sensors and the level of the solution can be corrected by adding an acid or alkaline solution. Usual pH values for growing are around 6.0 and 6.5. [10]

#### Soil Moisture

Water is the principal component of plant cells, and plants need water to perform photosynthesis, channel and transport nutrients, regulate temperature by transpiration and to keep their turgidity (shape). Much of this water is collected from the soil, through the roots, which means that soil moisture is an essential growth parameter for vegetables. [11]

Soil moisture can be regulated by watering the soil, the soil absorbs the water and this moisture level can be measured and studied.

#### Soil Temperature

Soil temperature is an important factor for knowing when to plant the seeds, since seeds have an ideal germination temperature that varies from species to species. In case the vegetables are planted too soon, with lower soil temperatures than the ideal for their species, they will grow slower and in case they are planted too late, with higher soil temperatures, there is the possibility that the excess heat will affect later plant growth. [12]

Soil temperature is a variable that depends on the season of the year, the hour of the day and also on the soil moisture, however with soil heating cables it's possible to increase soil temperature and keep it on the optimal levels for the target plant.

### 2.3.3 Security

Security is not related to plant growth conditions but instead with the security of the perimeter where the farm is located. There are many security system nowadays, video surveillance cameras with infrared night vision, motion detectors, sound alarms and laser perimeters. There is also no need to use on or another, a combination of several can be used in order to improve security.

In this project, security is established by the means of motion detection sensors. These motion detectors are a simple and cost-effective way of demonstrating the versatility and combined uses of wireless sensor networks.

### 2.3.4 Summary

Many control parameters were researched and studied, however, this project will focus only on controlling the light, relative humidity, temperature, soil moisture and security of the growth space.

## 2.4 Wireless Sensor Networks

Automation has improved many processes, enabling the production capacity to increase significantly while reducing workspace accidents, delivering a more uniform, controlled product and lowering overall production costs. Even though in certain activities the process is not completely automated, it's possible to reduce a large part of the workload through sensor networks with permanent control as is the case with farming and this particular project. The next logical evolution for sensor networks is to give them wireless capabilities which simplifies their installation, usage and material expenses due to not having a considerable amount of wiring.

Wireless sensor networks are not the perfect solutions to an imperfect process or surrounding environment, they are however, a complement to an already studied and fully functioning process, otherwise they won't reach the expected improvements and the process's overall efficiency will be lower, resulting in more expense for the farmer.

There are many commercial solutions available on the market, however these products are usually more expensive, not easily integrated into other systems, have components that are not easily interchangeable which need brand assistance which limits their usage and use proprietary software that is frequently abandoned by the company and gets outdated. This project attempts to demonstrate that automation of agricultural processes is not complicated and out of reach by constructing a wireless easy-to-build system that uses unexpensive components, is easily expandable and adaptable to each situation, and most important of all, achieves the desired objective.

### 2.4.1 ZigBee

ZigBee is a specification based on the Institute of Electrical and Electronical Engineers (IEEE) 802.15.4 standard developed in 1998 by ZigBee Alliance.

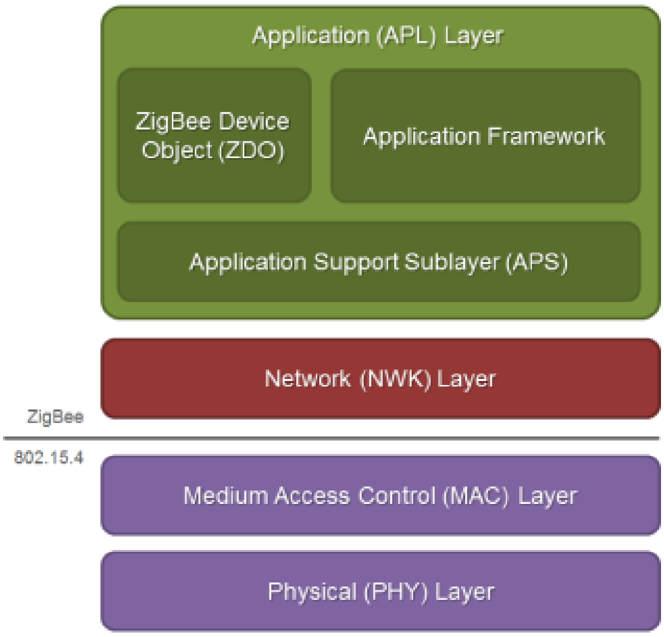
This protocol builds on top of the IEEE standard and defines a low cost, eficient and simple wireless communication technology that along with other characteristics which make it very appealing for wireless sensor networks and automation.

This protocol has certain advantages that make it particularly useful for automation, wireless sensor networks, such as easy setup and configuring of the devices, scalable mesh networks and adaptable to many different situations, control the networks remotely, possibility to increase and decrease network size by adding or removing devices, compatible with many products in the market ranging from indoor lights to door locks and garden appliances, has a low energy consumption and efficient operation.

Thus, this technology is often used in wireless automation, thanks to it's very low power consumption, wireless connectivity over long distances that allows unlicensed global usage that allows professionals and consumers alike to design and create their networks.

The IEEE 802.15.4 standard defines the Physical and Media Access Control (MAC) layers for the technology, essentialy placing it in the Low-Rate Wireless Personal Area Network (LR-WPAN) class, while ZigBee Alliance defines the Network and Application layers. A diagram with the different layers is shown on Figure 2.1.

Figure 2.1: ZigBee stack layers.




*Source:* `https://www.digi.com/resources/documentation/Digidocs/90002002/Content/Reference/r_zb_stack.htm`

### Physical Layer

The Physical (PHY) layer is the lowest layer and defines the method for the data transmission and reception such as the frequency, signal spreading technique, modulation and demodulation, bitrate, number of channels, channel rejection and power.

ZigBee devices have the capability to operate on different frequency bands depending on the geographical location where the network is being operated. The global unlicensed ISM frequency band (2.4 GHz) can be used or the region specific 868 MHz and 915 MHz bands in Europe and USA, respectively.

ZigBee is a low data rate protocol, noted for it's low power consumption in situations where high data rates are not required. The maximum data rate of the device varies with the operation frequency, with a theoretical maximum of 250 kbit/s for the 2.4 GHz frequency band and 20 kbit/s and 40 kbit/s for Europe and USA specific specific bands, respectively. In practice, due to the overhead of the ZigBee protocol, the speed for the global band is around half of the maximum, circa 125 kbit/s. [13]

The protocol uses Frequency Division Multiple Access (FDMA), dividing the operating frequency in several sub frequency bands, or channels. Additionaly, the number of channels also depends on the frequency band in which the devices are operating, with 1 channel for 868 MHz, 10 channels for 915 MHz and 16 non-overlapping channels for 2.4 GHz. For the global ISM band, each channel has 2 MHz bandwidth and is spaced 5 MHz apart. This information is summarized in Table 2.1:

Table 2.1: ZigBee Physical layer.

| Frequency [MHz] | | | | | | |
|---|---|---|---|---|---|---|
| Min | Max | Modulation | Bitrate [kbit/s] | Channels | Bandwidth [MHz] | Spread Spectrum |
| 868 | 868.6 | BPSK | 20 | 1 | 0.6 | DSSS |
| 902 | 928 | BPSK | 40 | 10 | 2 | DSSS |
| 2400 | 2483.5 | OQPSK | 250 | 16 | 2 | DSSS |

*Source:* [14]

A ZigBee device has a range between 10 and 100 meters indoor and over 300 meters by line-of-sight, which means that the devices must be pointing at each other without obstacles. Coupled with the possibility of having up to 65,000 devices in a single network, it's possible to have a very wide area coverage.

ZigBee devices can be divided according to their logical and physical operation. In relation to the logical operation, three types of ZigBee devices can be defined: [15]

- **Coordinator**

  The ZigBee Coordinator (ZC) coordinates the network, and is unique in the network since there can only be one. As the root of the network, it is responsible for initializing the network, distributing addresses to the other devices, defining crucial working parameters such as the channel of operation and storing vital information about the network. After initializing the network, ZC functions as an ordinary ZigBee Router (ZR).

- **Router**

  ZigBee Routers are capable of joining existing networks, receiving the data and forwarding it to other ZigBee devices, transporting the data packets from one router to another until it reaches the coordinator or the end device.

- **End Device**

  ZigBee End Devices (ZED) comprise the terminations of the network and are usually connected to sensors or actuators. These devices can only communicate with an associated router or coordinator, which means they can't communicate with other end devices. It's possible to connect an end device to one or more sensors, with a theoretical maximum limit of 240.

Based on physical operation, the 802.15.4 standard defines two types of devices: [16]

- Full Function Devices (FFD)
- Reduced Function Devices (RFD)

These two types of devices differ between themselves based on the amount of functionalities they possess. On one hand, FFD can use all of the functionalities and characteristics defined in the base IEEE standard and for this reason, they are used as coordinators and routers.

RFD on the other hand, need to be associated with FFD, have limited functionalities and therefore are normally used for end devices.

Additionally, FFD are always powered on, while RFD can suspend and power on depending on the work load. Thus, FFD are less energy efficient than RFD and are often connected to the mains power, while RFD can be connected to batteries since they use a low amount of power, greatly increasing the device's portability.

**Interference in the 2.4 GHz band** As noted in the previous section, the most commonly used frequency band for ZigBee communication is the global ISM 2.4 GHz band. This band is not exclusive to ZigBee communication and is also occupied by Wi-Fi, Bluetooth and Bluetooth Low Energy (BLE). Microwaves also emit powerful signals in this frequency band contributing to overall noise and interference across this specific spectrum interval and a great amount of devices comunicate in this band. An abbreviated comparison of the PHY layers of the protocols that communicate simultaneously on the 2.4 GHz band is present on Table 2.2.

Table 2.2: Comparison of protocols that communicate in the 2.4 GHz band.

| Protocol | Frequency [MHz] | Channels | Bandwidth [MHz] | Channel Separation [MHz] |
|---|---|---|---|---|
| ZigBee | 2400-2483.5 | 16 | 2 | 5 |
| Wi-Fi | 2400-2495 | 14 | 22 | 5* |
| Bluetooth | 2402-2480 | 79 | 1 | 1 |
| Bluetooth-LE | 2402-2480 | 40 | 1 | 2 |

**The channel separation between the $13^{th}$ and $14^{th}$ channel is 12 MHz.*

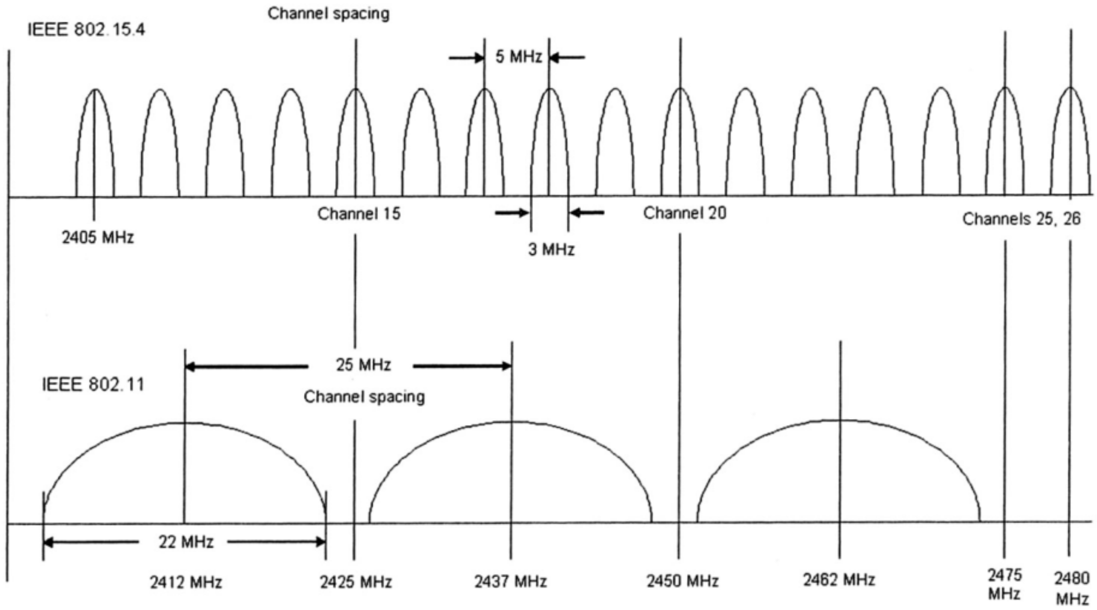
*Source:* [17]

In the case of Wi-Fi, that is a widely used protocol in present times, that shares the same frequency band as Zig bee, interferences can be created between the two protocols. Since the amount of smartphones with high speed Wi-Fi capabilities, wireless access points and routers is ever increasing, this might lead to increased communication errors in ZigBee networks since the presence of Wi-Fi might affect the delivery ratio, data rate and overall performance of ZigBee networks. [18]

The channels for both protocols are illustrated in Figure 2.2 (North American Wi-Fi). The two protocols have channels that overlap, which might raise problems when the implementation of both in the same space is desired. Even though there are channels that have minimal overlapping, there are still interferences, since some studies find that packet rate might decrease. [19] There are some workarounds to reduce interference, such as to configure the devices that use the two protocols to operate in separate fixed channels, however sometimes the other devices might be out of the user's control.

ZigBee devices are directed to low data rate networks which communicate infrequently, reducing the probability of communication problems, and have power level measurements to measure the correct transmission power

Figure 2.2: ZigBee and North American Wi-Fi channels.




*Source:* Crossbow.

in order to decrease interference for other devices. The protocol includes the possibility for a device to scan a channel and measure it's energy and interference to further decide whether it's a viable channel for the network.

ZigBee signals are Offset Quadrature Phase-Shift Keying (OQPSK) modulated and Direct Sequence Spread Spectrum (DSSS) is used. In comparison to Binary Phase-Shift Keying (BPSK), OQPSK is an M-ary quasi-orthogonal modulation and has great noise immunity, double the transmission rate since each bit carries two symbols instead of one, therefore half the bandwith required for the same bit error rate, more efficient in terms of bandwidth and lower error probability.

When compared to Quadrature Phase-Shift Keying (QPSK), the I and Q bits in OQPSK have half a symbol of offset, resulting in less undesired high frequency components caused by the abrupt change in phase that happens in QPSK, when the envelpe is inverted ($180^o$ change), lower Error Vector Magnitude (EVM) and higher bandwidth efficiency. [20]

Direct Sequence Spread Spectrum is a spread spectrum technique that spreads the signal and transmits it across different frequencies in the channel. The higher the spreading of the signal, the higher the signal's immunity to interference making it easier for it to coexist with other signals, especially narrow-band and also increases the signal's immunity to multipath interference. A downside of DSSS is that the transmission signals result in a signal with an increased bandwidth. [17]

### MAC Layer

The Medium Access Control (MAC) layer manages and handles the data transmitted and received by the devices, generates beacons used for association and disassociation of devices, implements Carrier Senser Multiple Access with Collision Avoidance (CSMA-CA) which is the access method for the network, implements Guaranteed Time Slot management (GTS), acknowledgement and validation of data frames and serves as interface between the PHY layer and the Network layer. [21]

For ZigBee coordinators, the MAC layer generates beacons, which is a special frame used to synchronize with other devices of the network, while for the rest of the devices the MAC layer synchronizes the devices with the coordinator.

CSMA-CA is responsible for avoiding collisions of packets between devices that share the same channel, before transmitting the devices scan the channel to verify if it's clear or there is communication, in case the channel is busy the device waits before retrying, ensuring that no more than one device is simultaneously communicating. [22]

Acknowledge and validation of dataframes is useful to reduce the amount of lost packets in the communication between two devices. When a device transmits to another device, the other device acknowledges the received packet and in case the transmitting device doesn't receive the acknowledgment (ACK) in a specified time frame, it will retry the communication several times until it times out.

Guaranteed Time Slot management allows devices to get assigned a time slot and is an optional mechanism used in low latency transmissions between the devices.

### Network Layer

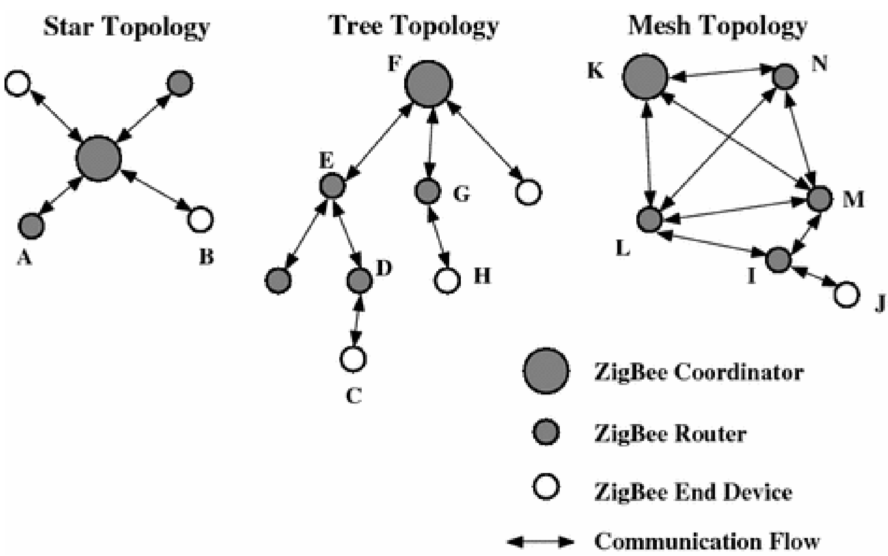
The Network (NWK) layer is responsible for interfacing the MAC layer and the Application layer. Functions of this layer include establishing the network and it's topology, assigning addresses to the devices, configuring each device for communication, authenticating the communication between the devices, allowing the devices to join and leave the network and to synchronize the nodes with each other. [21]

An energy scan is performed by the ZigBee coordinator when a network is being established in order to find the optimal RF channel. After a channel is chosen by the device, the network is attributed a unique identifier called the PAN-ID, a 16 bit number. In order for device nodes to communicate in a specific network, they have to be configured with this network identifier so that that device can associate with the network.

This layer also implements frequency agility, which allows the possibility, in the case a ZigBee coordinator detects interference, for it to use the full network to perform a interference scan and depending on the results, migrate the network to another channel.

It's possible to select different network topologies that can be adapted to each individual use case. Network topologies supported by ZigBee are represented in Figure 2.3: [23]

Figure 2.3: ZigBee network topologies.




- **Star** network usually consists in a coordinator surrounded by end devices. This is a simple topology, with minimum hops possible, that performs with lower latency and can be used in smaller areas where the communication distance doesn't exceed the device's range.

- **Tree** topology is more complete than the star topology and uses routers to extend the range of the network. There is still only one path for the data to go from source to destination.

- **Mesh** topology is the most complex of the topologies and has a coordinator, one or more routers and several end devices. In this network configuration, a mesh is created where data is passed in between devices, and with several paths for the information to reach it's destination. It is especially useful in situations where the distance between radios is higher than the range of the devices can offer because routers can pass the data between themselves until it reaches it's destination.

Since there are several possible paths for the data to follow, this topology is self-healing, which means that in the case of a device failure, an alternate path will be used. The mesh itself can also be extended by adding more devices, covering a larger area or smaller area by removing devices.

#### Application Layer

As illustrated in Figure 2.1, the Application (APP) layer is composed of three different layers. Application Support Sublayer (APS) is a layer that interfaces the NWK layer and the application layer with a variety of services that are used by the ZigBee Device Object (ZDO) and the application objects from each manufacturer and standardizes messaging between these devices for certain tasks. [15]

The Application Framework (AF) layer's purpose is to define various addressing objects that include profiles, clusters, and endpoints.

ZDO layer is located in between the APS layer and the AF layer, it provides the ability for devices to scan the network and discover other devicess, advanced network management capabilities and defines the device's type (capability) and to bind devices based on their types, such as a light switch and a lamp. [21]

### 2.4.2 ZigBee PRO

ZigBee PRO is an updated and upgraded specification of the ZigBee protocol developed in 2007 by ZigBee Alliance. While the two protocols share much of the same characteristics, there are some differences that differ between the two. For instance, the routing is different between the two protocols which causes some incompatibility issues for ZigBee PRO devices operating in a ZigBee network, restricting the device to a simple Zigbee end device and disabling routing features.

The latest protocol also specifies a different addressing mode, moving from the tree addressing in the ZigBee protocol that assigned addresses based on hierarchy to an addressing method that assigns addresses to the devices randomly and keeps track of the traffic to resolve conflicts.

ZigBee PRO includes a high security mode in which applies an additional layer of security when the network is not trusted.

In summary, ZigBee PRO is an updated protcol from the original ZigBee with more functionalities and a more stable operation, however it has more overhead and uses more processing resources. [23]

### 2.4.3 XBee ZigBee

ZigBee is a protocol and there are many implementations which use it available in the market. The chosen radio for the project is XBee ZigBee, which is a radio module from Digi International that utilizes the ZigBee PRO protocol. The module's characteristics can be found on Table B.1.

The radio module can be surface mounted (SMT) or through-hole (THT) and is installed onto XBee Grove Development Boards from Digi International which makes use of ZigBee capabilities and allows easy connection to Grove and other 4-pin sensors or actuators widely used with microcontrollers. The assembly works with 5 V, meaning it can easily be powered through USB, with a charger or battery cells for maximum portability.

### 2.4.4 Sensors & Actuators

Depending on the desired control parameter to control, ZigBee end devices can be integrated with a wide array of sensors and actuators with different functionalities.

#### Humidity

Hygrometers are tools and sensors used to measure the relative humidity in an environment.

Capacitive humidity sensors consist in a capacitor that contains an hygroscopic (holds water molecules) dielectric material placed between the two electrodes, usually plastic or a polymer. As the water molecules are absorved by the dielectric, the capacitance increases, resulting in a proportionally direct relation between the dielectric humidity and the relative humidity. [24]

Resistive humidity sensors are similar to capacitive humidity sensors, differing in the fact that they measure the resistance of the hygroscopic dielectric instead of the capacitance and that the relation between the resistance is inversely proportional to the relative humidity since the water molecules have a higher conductivity than air.

**Sensor:** Velleman MM102 Humidity Sensor is chosen to be used in the project. This sensor is equipped with a capacitive HIH-5030 sensitive element, can be used directly with the XBee and the datasheet is on Table B.7.

#### Luminosity

Light Dependant Resistors (LDR) are variable resistance resistors, which value decreases as the light intensity increases. These simple photo resistors can be manufactured to be sensitive for different wavelengths of light and are part of many different light sensors available on the market as well as home and garden applications.

Other electronic components suitable for light measuring sensors are photodiodes. As the light that reaches the photodiode increases, a current is produced in the photodiode that is directly proportional to the incident light.

To control the luminosity of the cultivation area, one or more lamps are used in order to maintain even lighting. Lamps can have different working modes with specific plant cycle phase usages, such as vegetating and flowering, some lights have different light spectrums and have different energetic needs. [25]

**Sensor:** Grove Light Sensor chosen, this sensor is equipped with a phototriode and the datasheet is on Table B.2.

### Motion Detection

Passive Infrared (PIR) sensors measure the radiated infrared (IR) light coming from nearby objects inside the detection range. These digital sensors are widely used in security applications where they are installed in a certain area or perimeter to detect intruders. PIR sensors can be coupled with other components including surveillance cameras, in order to activate the cameras only when there is motion, thereby saving virtual drive space and energy an also powerful lights or sound alarms to scare off potential trespassers.

Also used in automation to activate different components when motion is detected, such as lights and faucets to increase energy efficiency and reduce waste since when there is no movement, the components are automatically powered off.

The sensors can be engineered to work with specific IR light wavelengths depending on the objects to be detected. PIR sensors have a translucid plastic dome that covers a pyroelectric sensitive element that is sensible to the variations in IR radiation and generate an electric charge when exposed to a specific wavelength of infrared light. [26]

The PIR sensor used in the present project is the model SB612A and has adjustable sensibility and actuation time and it's datasheet displayed on Table B.6.

### Soil Moisture

Soil moisture sensors can range from simple budget sensors to full calibrated professional sensors. However, they can be divided in two main types, resistive and capacitive.

Resistive soil moisture sensors usually have two conductive probes, that are exposed to the elements and perfurate into the soil. These probes measure the resistance of the current that passes in between them, therefore, the higher the moisture in the soil, higher conductivity and the lower the resistance will be.

Advantages of resistive sensors are the lower cost and easier availability, however they are not durable since the electrodes are usually corroded due to the exposed contacts, especially if left working continuously due to the effects of the electric current. Over time, this deterioration decreases the sensor's accuracy, until the point when it needs to be completely replaced.

Capacitive soil moisture sensors have a completely different working mode, through capacitance as the name implies. These sensors usually only have one non-conductive probe that is perforated into the soil, preventing the corrosion issues frequent in resistive sensors. Capacitive sensors measure the variation in the dielectric (soil) and work on specific frequencies which allow them to be more sensitive to the water content and not as much by other components such as fertilizers and minerals.

To control the soil moisture, a water source is needed as well as a pump to deliver the water. There are different types of pumps that can pump liquids and the chosen pump for the project is a peristaltic pump.

Peristaltic pumps consist in a DC motor coupled to some rollers, through which a silicon tube passes. When the motor is activated, the compression by the rollers on the silicon tubing where the liquid is, causes it to flow inside the tubing, effectively pumping the liquid. These pumps have certain advantages, seen as the liquid is always contained inside the tubing, which allow for a greater types of fluids to pump and isolates the pump's inner workings from the fluid.

**Sensor:** The sensor chosen to measure the soil moisture is the SoilWatch 10 from the polish company Pino-Tech. This sensor is waterproof, which is an essential characteristic for outdoor electronic equipment. The SoilWatch 10 is a capacitive sensor which works with a frequency of 75 MHz. It's specifications are displayed on Table B.5.

**Actuator:** Velleman VMA447 peristaltic pump, which specifications are present on Table B.8.

#### Temperature

To measure the ambient temperature, it's possible to use a sensor that contains a thermistor. Thermistors are resistors with variable resistance that depends on the temperature, they can be Negative Temperature Coefficient (NTC), where the resistance is directly proportional to the temperature, which means the resistance increases when the temperature increases or Positive Temperature Coefficient (PTC), where the resistance is inversely proportional to the temperature.

**Sensor:** Grove Temperature Sensor (NTC), this is an affordable and easy to find sensor that makes use of a SMT NTC thermistor to read temperatures. There are many sensors on the market, however many have a 5 V working voltage which would imply the need for an additional step up DC converter, this sensor is compatible with the 3.3 V provided by the XBee. The datasheet for this sensor is displayed on Table B.4.

# Chapter 3

# Project

The main hardware components used in this project are the XBee ZigBee devices which have the ability to both receive and transmit data wirelessly, coupled to a variety of sensors for different applications that can be added, removed or exchanged according to each users' or culture species necessities. The sensors gather the data and control parameters to be sent to the coordinator which in turn outputs this information to the server that is running the software. After treating the values, the server inserts the obtained values in the database, analyzes them and in case they are not acording to the user's configuration, activates actuators in order to correct the values, effectively controlling the cultivating space's characteristics.

The diagram block for the network is illustrated in Figure 3.1. The sensors refer to any of the previously studied sensors and can be exchanged between themselves. A schematic of the radio module board is shown in Figure 3.2, where the different pins of the board are explicit.

Figure 3.1: Device network block diagram.

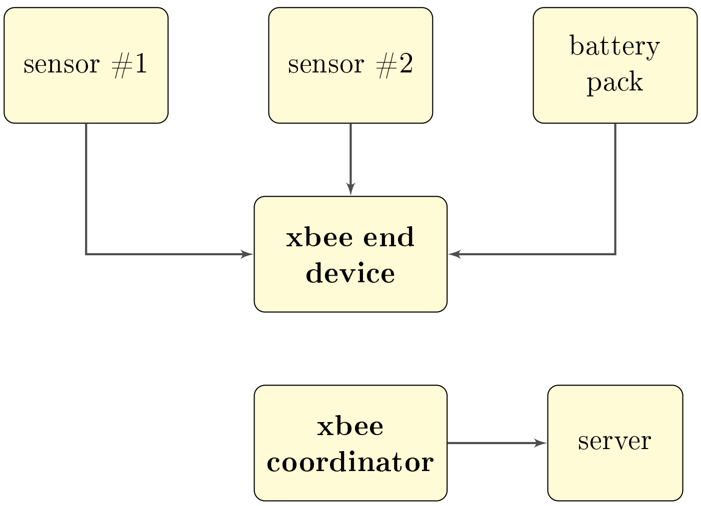
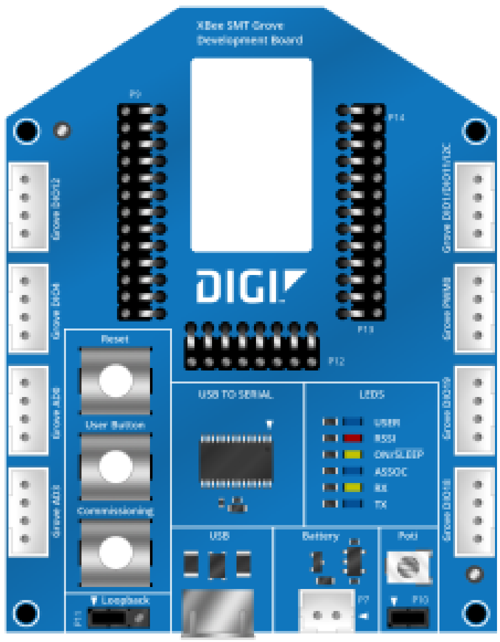


Figure 3.2: xBee radio module schematic.




This requires a multi-disciplinary project, with topics ranging from vegetable culture and bricolage for the physical build, electronics for the hardware and informatics for the background software that ties everything together.

## 3.1 Hardware

To demonstrate pure ZigBee functionalities, the radio modules are not attached to any microprocessors, thus, the XBee devices are working standalone which allows for a more energy and cost efficient solution, however, this working mode has some drawbacks. Due to the lack of a microprocessor, the XBee ZigBee modules have a limited number of pins and are not compatible with $I^2C$ sensors, effectively reducing the compatible sensors to mostly analog sensors. Analog sensors are less accurate and have less precise readings than $I^2C$ sensors for the same control parameters.

### 3.1.1 XCTU Configurations

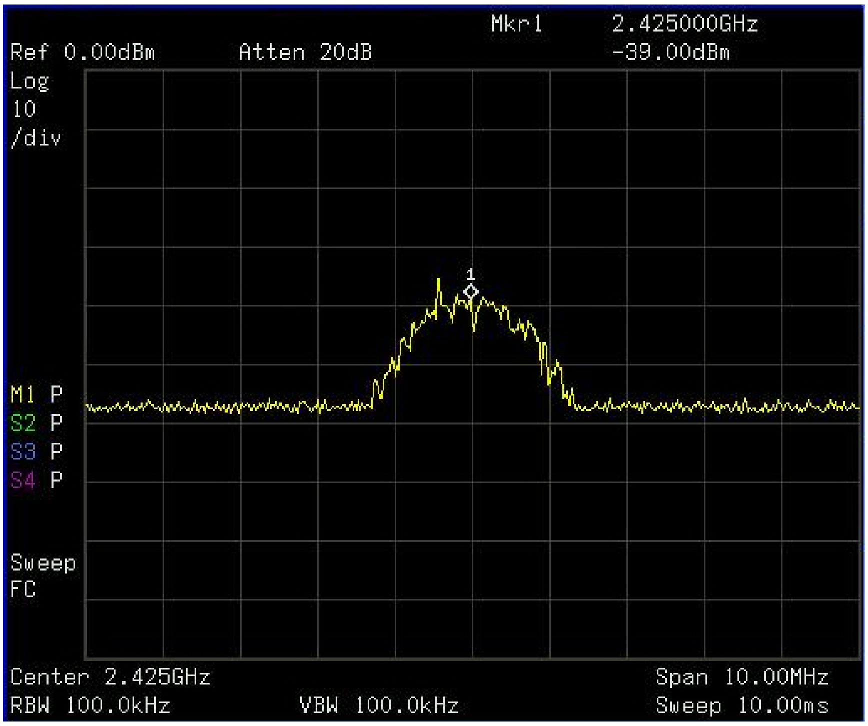
Before using the XBee modules, a brief configuration in the software XCTU provided by Digi International is necessary. XCTU is a software designed to easily manage and configure the XBee devices and provides simple configuration with a UI. This serves to configure both basic parameters like the channel, the destination addresses, if the device is a coordinator, and advanced parameters like delay and retry settings, number of hops and more ,of the device while it is connected to the computer by USB.

The minimum configuration needed in XCTU is to configure the PAN ID **ID**, verify if the channel **CH** on all devices is the same, set API Enable in the **AP** field in each device, enable coordinator mode in one of the devices and set the Destination Addresses **DH** and **DL** with the appropriate Source Addresses, **MY**. The devices are ready to begin communicating. [27]

### 3.1.2 Radio Tests

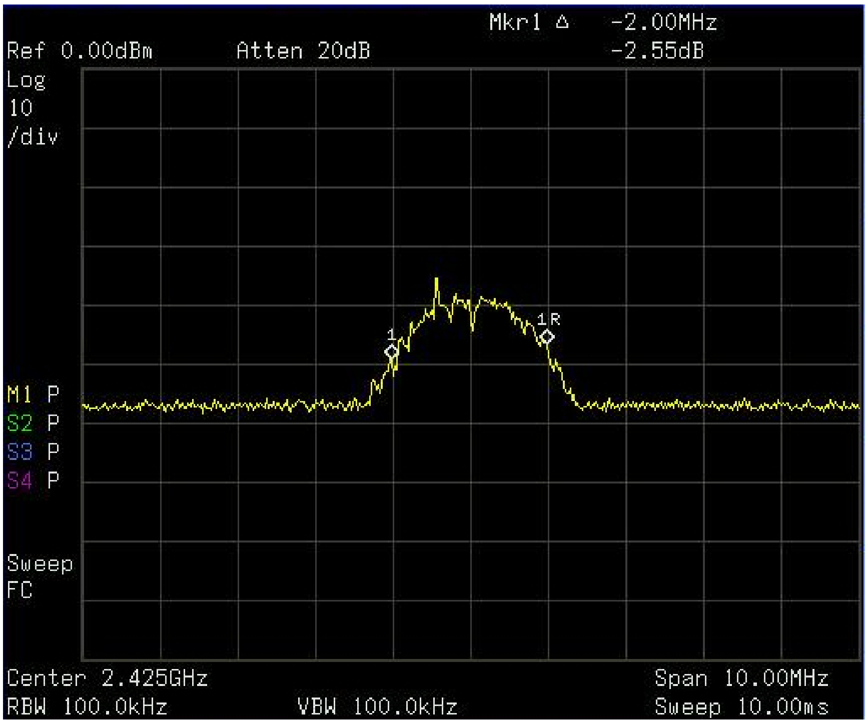
To measure the transmission signal with the least possible interference due to nearby Wi-Fi signals, the coordinator was installled in a small Faraday cage connected to a spectrum analyzer and a request for data sampling was made through the Management Suite developed. The resulting signal can be observed in Figure 3.3 and Figure 3.4.

Figure 3.3: ZigBee Tx signal power.




By analyzing the figures, it's possible to understand that the device is working on channel 5 of the global unlicensed 2.4 GHz band previously studied in Chapter 2, which is centered at 2425 MHz and the signal has 2 MHz channel bandwidth as expected.

Figure 3.4: ZigBee Tx signal bandwidth.




### 3.1.3 Sensors & Actuators

The sensors chosen require higher voltage than the 1.2 V supplied by the XBee ZigBee and have outputs with voltages superior than the voltages expected by the XBee devices, therefore these voltages are verified and adaptors manufactured so that the voltage values are compatible between the devices and the sensors or actuators. Failure to do so causes the sensor values to be wrong and shortens the sensivity range of the sensor (eg. temperature sensor reading max temperature at room temperatures).

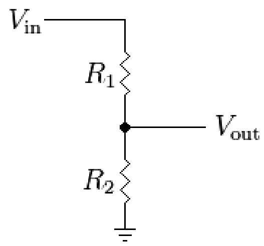
#### Voltage Adjustment

To decrease the voltage of the sensor output signals in order to be compatible with the XBee, voltage dividers are manufactured and employed. A voltage divider is a simple circuit composed of two resistors and is represented in Figure 3.5, with, $V_{\text{in}}$ as the sensor output voltage, $V_{\text{out}}$ as the XBee ADC input voltage, $R_1$ and $R_2$ the resistors which values are calculated.

The mathematical formula that allows to calculate the resistors needed for each sensor is the following:

$$V_{\text{out}} = V_{\text{in}} \cdot \frac{R_2}{(R_1 + R_2)}$$

Figure 3.5: Voltage divider.




For 3.3 V, the following values are obtained,

$$V_{\text{in}} = 3.3\,V$$

$$R_1 = 3900\,\Omega$$

$$R_2 = 2200\,\Omega$$

$$V_{\text{out}} = 1.19\,V$$

For 5 V, the following values are obtained,

$$V_{\text{in}} = 5\,V$$

$$R_1 = 3900\,\Omega$$

$$R_2 = 1200\,\Omega$$

$$V_{\text{out}} = 1.18\,V$$

The resistor values are chosen having in mind the closest resistor values available locally for purchase.

### Humidity

The humidity sensor used in this project is Velleman MM102, this sensor requires a minimum of 2.7 V and a maximum of 5 V. The sensor outputs a maximum of around 3 V.

### Luminosity

The light sensor from Grove requires between 3 V and 5 V.

### PIR

The SB612A PIR sensor used in the project has an operating voltage ranging from 3.8 V to 15 V with and output voltage of 3.3 V.

#### Soil Moisture

The soil moisture sensor requires between 2.8 V and 5.5 V and outputs 3 V.

The Velleman VMA447 pump used to water the vegetables requires 6 V to operate and is powered with a pack of four AA lithium cell connected in series, each AA lithium cell has 1.5 V. Between the XBee device and the pump a Grove relay module is installed, this allows the digital signals sent from the device to power the pump on and off.

#### Temperature

The temperature sensor from Grove requires between 3.3 V and 5 V and outputs a maximum voltage of 3 V.

## 3.2 Software

### 3.2.1 Database

The database is developed using *sqlite3* and contains all the data collected by the sensors, decision take by the alogrithm, the zones and device configuration as well as the treshold values of the parameters specific to each one that the user defines, the occasions where the treshold values are exceeded or fall short of the minimum value and the devices associated to the network. It is integrated on the program and the user can visualize or edit the database as desired without requiring any knowledge about databases.

The *sqlite3* database consists in a *.db* present in the server and is accessed everytime the user runs the wireless sensor network software.

The Entity-Relationship diagram of the database is presented in Figure 3.6. The database structure consists in five tables, a *data* table for storing data gathered by the sensors, a *devices* table that contains all the devices associated to the network, a *sensors* table that stores the device configurations, namely their connected sensors and their characteristics, a *logs* table that stores the decisions taken by the algorithm relative to the actuators or when a a value falls outside of it's treshold and a *zones* table that holds all the zones configuratios and their respective tresholds for each control parameter set by the user.

For the *zones* table the attributes are the following:

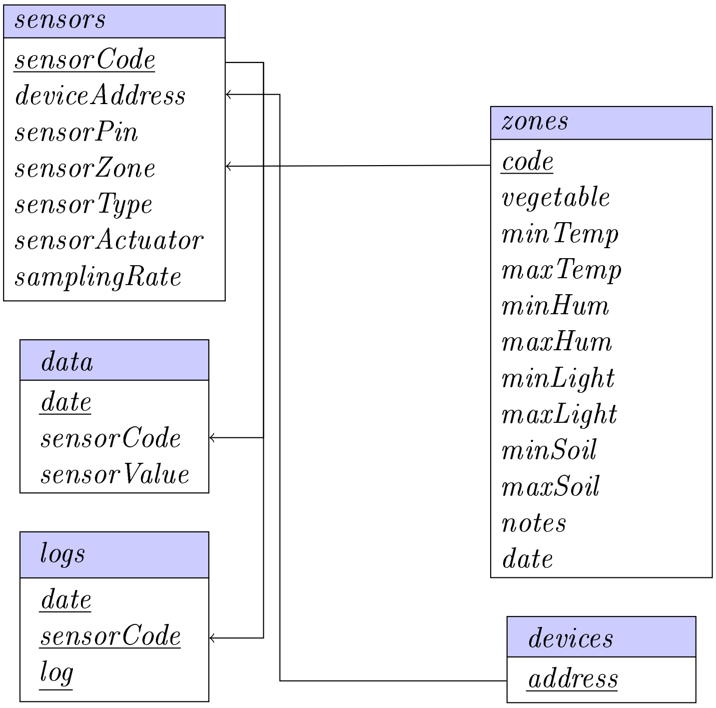
*code* is the code of the zone.

*vegetable* is the type of vegetable cultured in the zone.

*minTemp/ maxTemp* corresponds to the temperature tresholds.

*minHum/ maxHum* relates to the minimum and maximum humidity tresholds.

Figure 3.6: Database model diagram.




*minLight/ maxLight* is the minimum and maximum luminosity tresholds.

*minSoil/ maxSoil* is the minimum and maximum value for the soil moisture.

*notes* are an optional commentary to easily identify the zone.

*date* in which the zone was created.

The table *devices* contains the *address* attribute which is the 64 bit address of the XBee device.

For the *sensors* table the attributes are the following:

*sensorCode* is the code of the sensor.

*deviceAddress* is the device to which the sensor belongs.

*sensorPin* is the pin to which the sensor is connected.

*sensorZone* relates to the zone in which the sensor is located.

*sensorType* is the type of the sensor.

*sensorActuator* is the pin of the actuator associated for that sensor.

*samplingRate* defines the time rate for the sampling of the values from the sensor.

The attributes for the *data* table are the following:

*date* relative to the date of the sensor value sample.

*sensorCode* is the sensor that sampled the data.

*sensorValue* is the value obtained and mapped.

The *logs* table has the following attributes:

*date* relative to the date of the log.

*sensorCode* is the sensor that sampled the raised the log.

*log* is the occurrence and the decision taken by the software.

### 3.2.2 Management Suite

The management suite is the supporting software of the wireless sensor network and is developed using the programming language Python 3. The program is written on it's entirety on the software VIM, a text editor which can be adapted for Integrated Development Environment (IDE) use.

Python is a popular interactive and imperative programing language developed in 1991 by Python Software Foundation and more specifically by Guido Van Rossum. This programming language has a simple syntax and allows interfacing with a great variety of different libraries that can be used for many different functions, because of this Python has been increasing in popularity, especially within the scientific and academical community. Besides Python's simplicity and practicality, it's compatible with several Operating Systems (OS) and there is the possibility to expand Python's functions with C and C++ programming languages.

The program has a simple and easy to use graphical interface and contains several functionalities other than controlling the WSN, such as the statistical study of the behaviour of the network, by the means of graphing and historical data lists. The graphing can be related to one or more sensors of the same kind, from one or more zones, allowing for the maximum freedom of selection for the user. This means it's possible to easily compare specific kinds of values (eg. temperature) for all of the zones in the same graph, or for all of the temperature sensors of that zone in the same graph.

The highly interactive suite is interconnected to the database and allows for other useful functionalities, like the configuration of the program behaviour, such as which directories for the database, configuration of the XBee devices, configuration of the zone parameters and tresholds all intuitively inside the program without requiring the user to know how to program in *sqlite3*. The program is fully automated and doesn't need the user to make decisions while it's running.

The program is divided in several Python *.py* files. Each module is related to a specific function of the complete program and includes a set of functions related to that functionality. The structure of the software is the following:

*main.py*

*controla.py*

*ajuda.py*

*comunica.py*

*configura.py*

*historico.py*

*settingsFile.txt*

*userGuide.txt*

The *main.py* file consists in the main menu from which the users can select the specific function. The *controla.py* file is responsible for most of the database communications and it's function is to interface the database to the software, providing simple access to the user. In *ajuda.py* the functions relative to providing the user the help he needs to use the software are created. The functions to activate the network and sample the sensors as well as storing the values are in the *comunica.py* file. Basic configuration on the software is done in the *configura.py* file. Functions related to historic value viewing and analysis are present in the *historico.py* file.

Besides the Python files there are two text files associated with the software, *settingsFile.txt* and *userGuide.txt*, they are responsible for storing the settings of the software and User Guide, respectively.

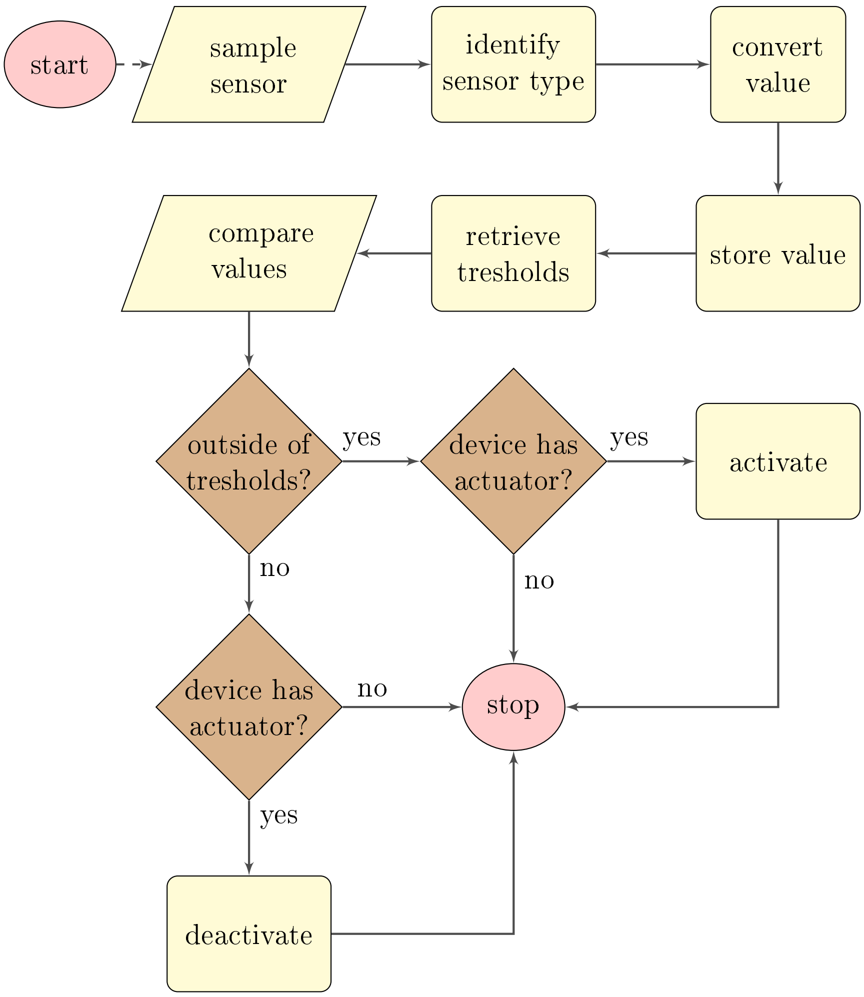
### 3.2.3 Algorithm

The XBee device's ADC pins reads the voltage that the sensors output and converts it to a value between 0 and 1023 which is difficult to interpretate, therefore this value needs to be properly treated before storing and using it for control purposes. The method to treat the sensor value depends on the sensor at hand, since each sensor has a different response to the changes in voltage and thus, has a different output. Moreover, the sensor values read different environment variables with different units, meaning individual formulas have to be used. Some of the formulas to convert the sensor values are available on the sensor's manual or datasheet.

The function that performs the conversion is `mapSensorValues` and is written in the *comunica.py* file. The value `sensorValue` is converted to `voltageValue` which is the sensor value converted to voltage, or converted directly according to the correct formula, resulting in `mappedValue`. This is performed as soon as the values are sampled, before storing in the database and performing the evaluations with the correct treshold values.

The algorithm is illustrated in Figure 3.7.

Figure 3.7: Algorithm flow chart.




### Voltage

Since the voltage is converted to 1.2 V, the voltage the XBee ADC inputs use, instead of the 3.3 V normally used, the calculations that use the voltage will not be correct, due to the value being lower than expected. To convert the sensor value `sensorValue` to the voltage value `voltageValue`, the following formula is applied:

```
voltageValue = sensorValue*(3300/1023)
```

The method is to get the ratio between the output by the XBee and the maximum value the XBee can read and multiply by 3300 which is the maximum output the sensor would provide without the voltage dividers in milivolts.

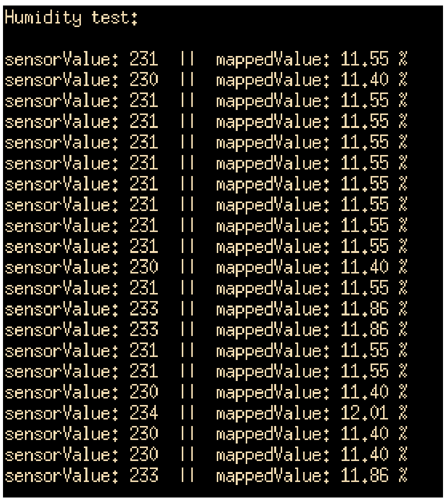
### Humidity

The formula to convert the sensor's output to relative humidity is found on the sensor's hygrometer datasheet. [28]

```
mappedValueU = (((voltageValue/1200)-0.1515)/0.00636)
mappedValue = mappedValueU/(1.0546-0.00216*T)
```

The second formula is to obtain the true relative humidity and uses $T$ which is the temperature to compensate, where a value of 20 is used. The test of the sensor was conducted indoors, next to a window with the sensor exposed to the elements and the result is shown in Figure 3.8.

Figure 3.8: Humidity sensor test.



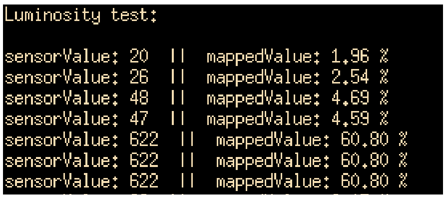
```
Humidity test:

sensorValue: 231  ||  mappedValue: 11.55 %
sensorValue: 230  ||  mappedValue: 11.40 %
sensorValue: 231  ||  mappedValue: 11.55 %
sensorValue: 231  ||  mappedValue: 11.55 %
sensorValue: 231  ||  mappedValue: 11.55 %
sensorValue: 231  ||  mappedValue: 11.55 %
sensorValue: 231  ||  mappedValue: 11.55 %
sensorValue: 231  ||  mappedValue: 11.55 %
sensorValue: 231  ||  mappedValue: 11.55 %
sensorValue: 231  ||  mappedValue: 11.55 %
sensorValue: 230  ||  mappedValue: 11.40 %
sensorValue: 231  ||  mappedValue: 11.55 %
sensorValue: 233  ||  mappedValue: 11.86 %
sensorValue: 233  ||  mappedValue: 11.86 %
sensorValue: 231  ||  mappedValue: 11.55 %
sensorValue: 231  ||  mappedValue: 11.55 %
sensorValue: 230  ||  mappedValue: 11.40 %
sensorValue: 234  ||  mappedValue: 12.01 %
sensorValue: 230  ||  mappedValue: 11.40 %
sensorValue: 230  ||  mappedValue: 11.40 %
sensorValue: 233  ||  mappedValue: 11.86 %
```

### Luminosity

The appropriate formula to convert this specific sensor to lux is not available, however, it is still possible to control the network using the percentage of maximum light the sensor can read.

The light sensor test is conducted at night indoors, two samples taken with the lights off, two samples with the lights on and two samples with a flashlight close to the sensor. The obtained results can be seen in Figure 3.9.

Figure 3.9: Luminosity sensor test.



```
Luminosity test:

sensorValue: 20  ||  mappedValue: 1.96 %
sensorValue: 26  ||  mappedValue: 2.54 %
sensorValue: 48  ||  mappedValue: 4.69 %
sensorValue: 47  ||  mappedValue: 4.59 %
sensorValue: 622  ||  mappedValue: 60.80 %
sensorValue: 622  ||  mappedValue: 60.80 %
sensorValue: 622  ||  mappedValue: 60.80 %
```

### Motion Detection

The motion detection sensor is not connected to the ADC pin, but to a digital DIO pin. Consequently, it does not output a variable value, it either outputs *LOW* or *HIGH* when activated.

The test is conducted indoors after adjustments in the potentiometers of the sensor, there is a potentiometer for adjusting the sensivity, another for the delay time, which is the time the sensor remains activated after detecting motion and a potentiometer for the darkness adjustment. After extensive testing the PIR sensor does not behave as expected, it can be activated by simply adjusting the darkness adjustment and will not change state to *LOW* as quick as it should. In case the darkness adjustment is too low, it will not activate with motion, but if adjusted in a specific position it activates when motion is detected.

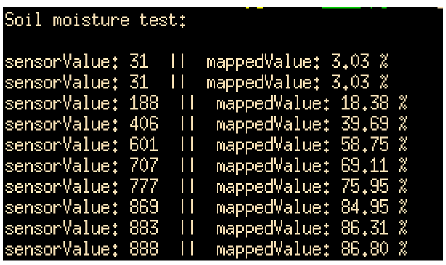
### Soil Moisture

To convert the soil moisture sensor, that outputs a value of 0 when fully dry and 1023 when completely wet, the sensor value is converted to the percentage between the obtained value and the wet condition value. As such, the formula is the following:

```
mappedValue = (sensorValue/1023)*100
```

The soil moisture sensor test illustrated in Figure 3.10 was conducted by slowly inserting the probe inside a cup with water, when the probe is almost submerged, the value is close to the maximum the device can read.

Figure 3.10: Soil moisture sensor test.



```
Soil moisture test:

sensorValue: 31  ||  mappedValue: 3.03 %
sensorValue: 31  ||  mappedValue: 3.03 %
sensorValue: 188  ||  mappedValue: 18.38 %
sensorValue: 406  ||  mappedValue: 39.69 %
sensorValue: 601  ||  mappedValue: 58.75 %
sensorValue: 707  ||  mappedValue: 69.11 %
sensorValue: 777  ||  mappedValue: 75.95 %
sensorValue: 869  ||  mappedValue: 84.95 %
sensorValue: 883  ||  mappedValue: 86.31 %
sensorValue: 888  ||  mappedValue: 86.80 %
```

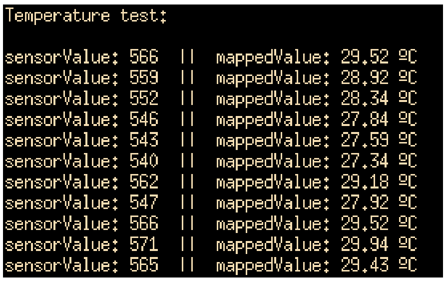
### Temperature

The temperature sensor's conversion formula is available in the sensor's datasheet. [29]

```
B = 4275
R0 = 100000
R = 1023.0/sensorValue-1.0
R = R0*R

mappedValue = (1.0/(math.log(R/R0)/B+1/298.15)-273.15)
```

The temperature sensor was tested indoors, both in the shadown and directly in the sun, the results are pictured in Figure 3.11.

Figure 3.11: Temperature sensor test.



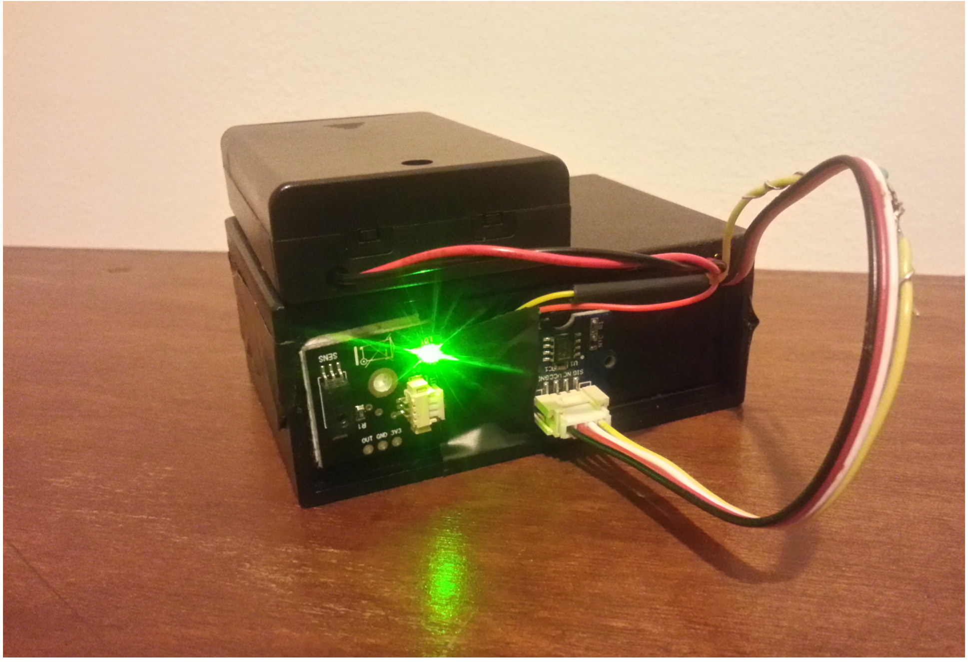
```
Temperature test:

sensorValue: 566  ||  mappedValue: 29.52 ºC
sensorValue: 559  ||  mappedValue: 28.92 ºC
sensorValue: 552  ||  mappedValue: 28.34 ºC
sensorValue: 546  ||  mappedValue: 27.84 ºC
sensorValue: 543  ||  mappedValue: 27.59 ºC
sensorValue: 540  ||  mappedValue: 27.34 ºC
sensorValue: 562  ||  mappedValue: 29.18 ºC
sensorValue: 547  ||  mappedValue: 27.92 ºC
sensorValue: 566  ||  mappedValue: 29.52 ºC
sensorValue: 571  ||  mappedValue: 29.94 ºC
sensorValue: 565  ||  mappedValue: 29.43 ºC
```

### Enclosure

After properly configured and with the equipment connected, the devices are installed inside a customized plastic case to protect them from the elements. The case of the device has a batttery pack attached that powers the XBee.

The dimensions of the case are 89.2 mm of length 64.5 mm of width and 35.8 mm of height, which makes the device easily portable due to the small dimensions. A device equipped with the humidity sensor and the temperature sensor is pictured in Figure 3.12.

Figure 3.12: Device with humidity and temperature sensor.



## 3.3 Growhouse

In order to accurately demonstrate the project's capabilities, a growhouse is constructed. The growhouse contains a parsley plant (Petroselinum crispum), and is equipped with the sensors and actuators used throughout the project, allowing for a simple and transparent view of the automation process and providing a stable and protected environment for the growth of the plant.

To build the growhouse, plywood boards are used for the bottom structure and wooden bars for the structure which will support the sensors and the lamp. The plant is installed in the middle of the tray, directly under the light source, allowing for space for the water tank, the humidifier and the fan to be installed on the surroundings of the pot.

The growhouse's dimensions are chosen according to the plant's size and the size of the boards available locally, however they offer plenty of space for the purpose of demonstration:

$$300\,L * 600\,W * 600\,H[mm]$$

with $L$ as the length, $W$ as the width and $H$ as the height.

With the materials cut, pictured in Figure F.1, the wooden components are lightly sanded to provide for better glue addhesion due to a smoother interface and remove rough edges. After the sanding is the mounting of the base, followed by mounting the structure on top.

The growhouse structure is displayed in Figure F.2. It is now capable of supporting the farming operation, with it's ease of modification, allowing for a versatile and customizable experience to the grow at hand.

Next step is to add the rest of the elements such as the plant and electronic components to take detailed measurements and build a support for the device. The elements used are an XBee device with a soil moisture sensor coupled to the water pump and an humidity sensor coupled to the humidifier. The result obtained can be observed on Figure F.3 and Figure F.4.

# Chapter 4

# Results

## 4.1 Wireless Sensor Network

## 4.2 Management Suite

### 4.2.1 Main

The main menu provides the user an easy and intuitive access to the program's functionalities with a minimalist UI. The menu window is displayed in Figure D.1 and the flowchart for it's operation is represented in Figure D.2.

When a button is pressed, depending o the functionality the user chose, a window opens and provides access to a set of related functions, these can range from historic data visualization from exiting the program and activating the wireless sensor network.

### 4.2.2 Start

The *Start* button activates the wireless sensor network. The coordinator is detected by the server, the network scanned for neighbouring devices, remote devices configured acording to the configuration parameters stored in the database and the cyclic sampling process is initialized. The values obtained are then stored in the database and compared with the tresholds, depending on the situation, different actuators are activated.

By pressing the button, a window displaying the latest sensor value readouts along with the date they were taken opens to provide real time observation of the state of the network. This window is displayed in Figure D.3 and the flowchart for this operation is on Figure D.4. After activating the wireless sensor network, the program runs independently of the user.

To terminate the wireless sensor network, the *TERMINATE* button must be pressed. This button terminates the network by configuring the active XBee's digital pins to *LOW* and closing all the communications with the database and the devices, ensuring a safe closure of the network and ease of operation for the user.

### 4.2.3 Network Check

The user can manually check the network for operating devices by pressing the *Network Check* button from the main menu. This is only makes sense if an XBee device is connected, otherwise all devices will appear as inactive.

The flow chart for this operation is represented in Figure D.6, the coordinator connected to the server performs a scan of the network, discovers the active devices and compares them to the devices configured in the database. In the event of a device failure or inoperability it won't be found by this network scan, however it is present in the database which will trigger a warning to the user. The user can then verify the device's conditions in order to activate it again, this is particularly useful in the event of a device losing power and needing the batteries replaced. This situation is shown in Figure D.5.

### 4.2.4 Control

In this section, the user can visualize the previous defined zone tresholds and device settings or configure new zones and associate new devices. Complete information of the zones and devices is displayed on the tables. The graphical interface is represented in Figure D.7 and the flow chart for this window is represented in Figure D.8.

Adding new zones is done in the window shown in Figure D.9a is possible by pressing the *Add*, deleting zones with the *Delete* button, or editing the previous configured zones by pressing *Edit* that opens the window in Figure D.9b. The flow charts for the addition of zones and edition of zones are illustrated in Figure D.10a and Figure D.10b, respectively.

Other than the zones, the devices are also displayed in another table down below with the same functionalities as the previous zone table, that is, the possibility of deleting or editing the defined devices, with the exception of not having an *Add* button but a *Discover* button instead. Pressing this button triggers a scan of the network and the associated devices. At the same time, the program compares the devices found in the scan of the network with the devices defined previously in the database. Each new device is displayed to the user as pictured in Figure D.11a and after being configured in the window shown in Figure D.11b, the devices are inserted in the database. The flow chart for this process is pictured in Figure D.12. The configuration of the devices is simple and consists in associating the I/O pins with a zone and a type of sensor.

Editing a device configuration is possible by selecting the device andpressing *Edit*, which opens the device configuration window shown in Figure D.13.

Contrary to the zone editing window, the device editing window doesn't give the user much freedom to configurate and since each device is associated to a particular zone, the only options to choose given to the user are based on the zones that are already configured, thus making the process of configuration simple and with less chance of human error when configuring.

After the configuration of a device, a code for each connected is created, this code is used to quickly identify and locate that particular sensor. The code structure is *Zone-SensorTypeSensorNumber* and depending on how many sensors of the same type already exist for that particular zone, the code is auto generated by the software. An example of this situation is if there are two humidity sensors in zone A1 and the user configures another humidity sensor for zone A1, the sensor's code will be A1-H3. This process is automatic and the user doesn't need, or can, to configure the code for the sensors. The sensor types include *T* for temperature, *H* for humidity, *SM* for soil moisture, *L* for light and *PIR* for the proximity sensor.

Each column from both tables can be rearranged in a increasing or decreasing order, simply by pressing the column header, one or two times depending on the the preferred order. This allows the user to easily study and compare all the parameters in the configuration of the wireless sensor network.

### 4.2.5 History

The *History* page is illustrated in Figure D.17 and displays the historic values obtained by the WSN during it's operation and consists in two tables, *Data* and *Logs*. The values from the tables can be plotted graphically or consulted in a list, in the case of the latter, they can be rearranged in an increasing or decreasing order for each parameter simply by pressing on the column of the parameter. The flow chart for this window is represented in Figure D.14

In the *Data* table, the values collected by the sensor or sensors from the network are presented to the user, along with the date and time of the sampling and the code of the sensor that sampled the value. By the sensor code it's possible to identify the zone and type of the sensor. The data collected by the sensors is visualized graphically by the means of a scatter plot with different colors for each sensor.

In the *Logs* table, the logs are displayed. Logs are created everytime a control parameter exceeds or falls short of the treshold value defined for the zone it is located and consists in the date and time it was triggered, a message indicating the action taken, depending on the parameter itself (example: soil moisture below minimum level, turning on water pumps) and the sensor code for the sensor that registered the value. With this information, a registry is created that the user can study to know the weakest points on the vegetable farm in order to further improve efficiency. Visually, logs are represented in the form of an histogram, which counts the logs for that particular sensor or sensors for each day.

To graphically plot the data it's necessary to press the *Visualize* button on the right of the desired table. A new window opens up with a radio button for each control parameter, humidity, luminosity, soil moisture or temperature. After selecting one of the radio boxes, the configured sensors for that control parameter are displayed on the right, as the Figure D.15 represents, and it's possible to select one or more sensors. In the case of a multiple sensor plot, the sensors are not required to belong to the same zones and the graphs are superimposed on the same window. The flow chart for this process is illustrated in Figure D.16. An example plot of the logs of a sensor is shown in Figure D.18, the buttons below the plot are relative to the plot functions such as zoom, pan, view reset and storing the graphical plot as an image on the computer.

### 4.2.6 Help

The *Help* section contains documentation associated to the usage of the program, a complete User Guide, including a Frequently Asked Questions (FAQ) with the most common actions, which the user can resort to when in doubt. This page is exceptionally helpful since the program has many functions and features that can be hard to remember without a guide.

Figure D.19 and Figure D.20 represent the *Help* page and it's flow chart, respectively.

The *User Guide* is available in a written version in Appendix E.

### 4.2.7 Settings

The *Settings* page allows the user to configure vital software parameters like the database directory, the communication port where the coordinator is connected that are used by many functions of the software and it also lets user know which ZigBee channel the network operates on. This page is displayed in Figure D.21 and the process is represented in the flowchart in Figure D.22.

The configuration is stored in a text file *settingsFile.txt* present in the program's directory, which consists in three lines, one for each parameter. To alter the configuration the user can edit an existing file by editing the desired information in this window and then saving it by pressing *Save* or import a file by pressing the *Import* button. In case there is no configuration file, the program will not function correctly, however to create a new file the user simply needs to input the configuration and press *Save*, the file will automatically be created. The flowchart for these operations is shown in Figure D.23.

### 4.2.8 Exit

The *Exit* button quickly terminates and exits the program.

## 4.3 Growhouse

The growhouse obtained can be used for an indoor grow of a small plant or an array of smaller plants due to it's dimensions and the capabilities for protection and organizing of the grow space it offers, combining all the elements in one place, it is perfect for the demonstrative purposes of it's construction.

## 4.4 Discussion

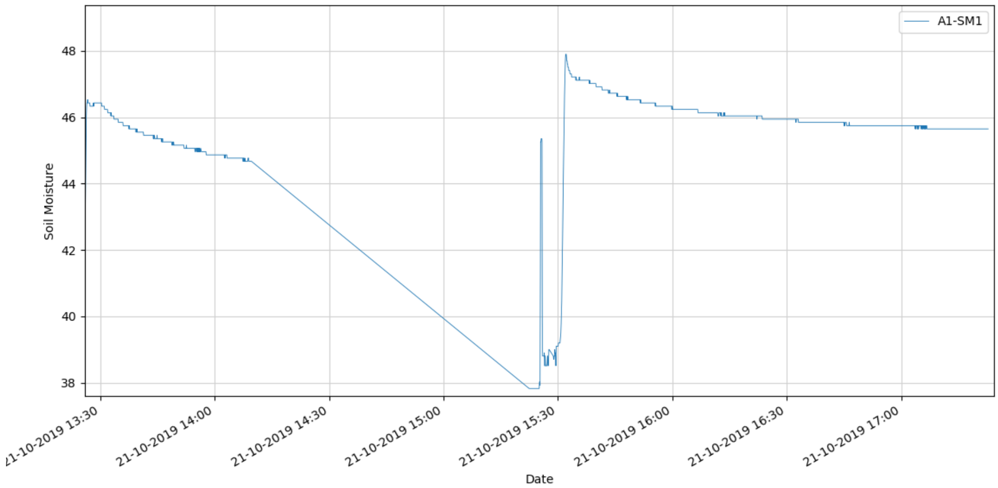
The Management Suite provides the user the possibility of customizing a wireless sensor network, it is not hardcoded into a particular device or configuration and is easy to be used by a person that is not familiar with programming. The software acts as an interface to the database and it's possible to create as many different areas as desired, with the exact values for each control parameter and simple device association and configuration by pressing buttons, in case of doubt there is a User Guide on the software for help. Considering this, it's possible to install the devices in a variety of situations and the obtained growhouse is tested with an XBee device equipped with the soil moisture sensor and the humidity sensor, as for actuators, it is connected to the water pump which contains the respective reservoir, relay module and 4xAA battery pack.

The soil is initially in an almost dry state, which the soil moisture sensor reports that is decreasing in water content at a slow pace. When the sensor detects that the soil is too dry for that particular zone, in this case the parsley plant, it activates it's actuator and the water pump initiates the watering process of the plant. The soil moisture level of the plant increases until it reaches the desired levels while the values are displayed for the user.

After the process is finished, a study can be conducted to better understand it's characteristics using the graphical representations. Data is valuable and studying the process allows to improve it. By knowing the ratio of water consumption depending on the temperature, humidity, pot size, soil type, plant age and vegetable species, a test bed can be conducted, with the conditions kept closer to the optimal during specific times and seasons, possibilitating a prediction of the plant behaviour and allowing experiments with other environmental conditions or soil types, for example, to compare with the objective of better understanding the plant response.

In the test case performed, which analyzes the variation in soil moisture values, illustrated in Figure 4.1, the growhouse is capable of automatically watering the plant, providing the basic needs to be self-suficient. It's possible to observe the water content in the soil decrease due to filtering and plant water consumption, until the minimum treshold is reached, after which, the water pump is activated and the water content in the soil increases. With due study the plant can be fed exactly the amount of water it needs and when it needs, reducing stress for the plant.

Figure 4.1: Variation in soil moisture levels and water pump activation.




The proposed objective of the project was reached, using the software developed it was possible to personalize and increase the efficiency in the watering process for the plant, also removing most of human interaction except for routinely checking for the device operation and refilling the water reservoir. Taking into account the fact that the test was done in a living area without advanced equipment, the end results are not as good as they could be, since the area itself is not studied or equipped for the purpose and is difficult to keep optimal environmental conditions with the existing equipment. However, it is still possible to retain knowledge from this test, thus the soil moisture test was chosen as it is easier to demonstrate.

Other conditions can be equally controlled, if the temperature sensor is used, if excessive temperature or insufficient temperature is detected, activating the fan or a heater, depending on the circumstance, effectively returns the values to the configured interval.

In the case of humidity, both a humidifier such as the one used in this project or a dehumidifier coupled to a relay module can control the humidity parameters of the grow space. To have stable levels of humidity, a controlled environment is necessary, or else the system has an increased dependency in the actuators, elevating electrical energy consumption. The humidifier used in this project is not adequate to alter the humidity levels of a small room unless properly enclosed in a space of very small dimensions.

It's possible to control the light, however without a dimming device, in the case the light is insufficient, the lamp would simply turn on and not provide a specific level of luminosity.

Although the system monitored and controlled the parameters using the configured values, the values the sensor obtain are not be the most accurate. Due to the incorrect voltage feeding of the sensors, the voltage dividers and the software formulas there are errors that affect the final value. Calibration and adjustment of the formulas is necessary in order to obtain value samples closer to the true values.

The end result of the project is positive, however there is further space for improvement which is reviewed in the next chapter.

# Chapter 5

# Conclusion

During the project, a study about the ZigBee protocol and a practical application of itself was conducted, there was a theoretical study on the subjects that relate to the project and based on the knowledge obtained a set of tools were developed with the intent of demonstrating the capabilities of the protocol by the means of monitoring and controlling an hypotethical vegetable farm in a diminiute, indoor environment. This simple approach could be applied in many households and small farms as a method of lowering waste and after the investment, spending less on expenses.

The concept can be applied from small indoor grows to larger scale agricultural companies and farmers throughout the world which desire to have more control and provide better environmental conditions to their crops in order to achieve increased yields and harvests. Wireless sensor networks, when correctly applied can be deployed in a variety of situations and use cases, particularly in agriculture, where it brings higher profits at a lower cost and lower ecological impact for commercial growers.

The project was successfull and using the tools developed it's possible to effectively monitor and control the parameters of a certain grow zone. These tools consist in the assembled devices that contain the radios and the sensors or actuators, a software that can run independently of the user and a database that is stores the values and allows for statistical analysis of the data obtained by the means of graphical representations.

Even though the system performs as expected there are some issues that need to be addressed. These issues mostly affect the performance and precision of the sensor value sampling and control of the network. Due to this, the value readings obtained from the sensors are not as accurate as they should, however, the wireless sensor network still does it's purpose.

It's possible to conclude that the application of wireless sensor networks can bring many benefits, not only in agricultural situations but in other processes that depend on certain characteristics that are easily controlled with electric equipment.

## 5.1 Future Work

As a continuation of the present work, both the software and hardware of the project can be improved, to provide more functionalities and a ease of operation. Regarding the software, a website that manages and monitors the wireless sensor network could be implemented. This website could be accessed remotely by the means of a password or user account and would mimic the developed software, in particular the *Control* and *History* sections of the Management Suite, allowing for a remote analysis of the sensor network instead of using the server itself.

In relation to the hardware, the addition of a microcontroller for specific devices would benefit the project since it would simplify connections by eliminating coupling issues between the sensors and the device reducing the power losses and conversion errors associated while at the same time increasing sensor reading accuracy and more stable operation. The addition of the microcontrollers would however imply a substancial increase in cost for the total project. However, this was not the objective of this project, thus some difficulties were encountered and extra steps were taken, such as installing voltage dividers, to ensure the devices and sensors were functioning correctly.

The quality of the hardware itself can be improved, simple equipment was used for demonstrative purposes, however some of this equipment is not the most adequate for real world usage, or the most accurate. Higher quality equipment would undoubtfully improve the quality of the sensor network but on the other hand increase the costs. The core of the system is implemented, the rest of the system can be changed according to the use case and objectives.

# Bibliography


[1] R. McDougall, P. Kristiansen, and R. Rader, "Small-scale urban agriculture results in high yelds but requires judicious management of inputs to achieve sustainability," pp. 129–134, December 2018.

[2] FAO, *The State of the World's Land and Water Resources for Food and Agriculture - Managing systems at risk.* Food and Agriculture Organization of the United Nations, Rome and Earthscan, London, 2011.

[3] M. S. Dhaliwal, *Handbook Of Vegetables.* 2017.

[4] A. Rogers, E. A. Ainsworth, and A. D. Leakey, "Will elevated carbon dioxide concentration amplify the benefits of nitrogen fixation in legumes?," *Plant Physiology*, November 2009. `http://www.plantphysiol.org/content/151/3/1009/`.

[5] T. Krishnamurti and D. B. Enfield, "Climate," May 2019. `https://www.britannica.com/science/climate-meteorology/`.

[6] S. S. Wyer, *A treatise on producer-gas and gas-producers.* McGraw-Hill, second ed., 1906.

[7] B. N. Taylor and A. Thompson, *The International System of Units (SI).* National Institute of Standars and Technology, March 2008.

[8] OpenStax, *Biology.* August 2012. `https://bio.libretexts.org/Bookshelves/Introductory_and_General_Biology/Book%3A_General_Biology_(OpenStax)/`.

[9] W. H. Allaway, "pH, Soil Acidity and Plant Growth," `https://naldc.nal.usda.gov/download/IND43894850/PDF/`.

[10] Earth-Kind, "Natural Plant Nutrients: For Landscapes and Gardens...," `https://aggie-horticulture.tamu.edu/earthkind/files/2010/10/naturalnutrients.pdf`.

[11] University of Florida, "What makes plants grow?," tech. rep., January 2019.

[12] N. S. A. Sabri, Z. Zakaria, S. E. Mohamad, A. B. Jaafar, and H. Hara, "Importance of Soil Temperature for the Growth of Temperate Crops under a Tropical Climate and Functional Role of Soil Microbial Diversity," *Microbes Environ*, pp. 144–150, April 2018. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6031386/.

[13] Digi, "XBee 802.15.4 Protocol Comparison," tech. rep.

[14] ZigBee Alliance, "ZigBee PRO." https://zigbee.org/zigbee-for-developers/zigbee-pro/.

[15] Digi, *XBee® ZigBee® Mesh Kit User Guide*, February 2018.

[16] ZigBee Alliance, "ZigBee Specification," tech. rep., August 2015. https://zigbee.org/zigbee-for-developers/zigbee-pro/.

[17] F. Mazda, *Telecommunications Engineer's Reference Book.* Butterworth-Heinemann, March 1993.

[18] R. G. Garroppo, L. Gazzarrini, S. Giordano, and L. Tavanti, "Experimental assessment of the coexistence of Wi-Fi, ZigBee, and Bluetooth devices," August 2011.

[19] M. D. Abrignandi, C. Buratti, L. Frost, and R. Verdone, "Testing the impact of Wi-Fi interference on Zigbee networks," *Euro Med Telco Conference*, November 2014.

[20] S. Chattopadhyay and S. K. Sanyal, "Comparison of Performance Metrics for QPSK and OQPSK Transmission Using Root Raised Cosine & Raised Cosine Pulse-shaping Filters for Applications in Mobile Communication," *International Journal of Computer Science and Information Security*, pp. 106–112, 2009.

[21] ZigBee Alliance, *XBee®/XBee-PRO S2C ZigBee® User Guide*, June 2019. http://www.digi.com/resources/documentation/digidocs/pdfs/90002002.pdf.

[22] ZigBee Alliance, "ZigBee and Wireless Radio Frequency Coexistence," tech. rep., June 2007. http://www.es.ele.tue.nl/education/ci/project/files/lab2/datasheets/ZigBee_and_Wireless_Radio_Frequency_Coexistence.pdf.

[23] A. Elahi and A. Gschwender, *ZigBee Wireless Sensor and Control Network.* 2009.

[24] Rotronic, "The Capacitive Humidity Sensor," tech. rep.

[25] E. Darko, P. Heydarizadeh, B. Schoefs, and Sabzalian, "Photosynthesis under artificial light: the shift in primary and secondary metabolism," *Philos Trans R Soc Lond B Biol Sc*, March 2014. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3949401/.

[26] R. Biswa and S. Gyeltshen, "Passive Infrared (PIR) Sensor Based Security System," *International Journal of Electrical, Electronics and Computer Systems*, June 2013.

[27] Digi, *XCTU User Guide*, September 2019.

[28] Honeywell, *Installation Instructions for the HIH-5030/5031 Series Humidity Sensors.* https://sensing.honeywell.com/HIH-5030-001-humidity-sensors.

[29] Seeed Studios, *Grove Temperature Sensor User Manual V1.0*, September 2015.

[30] Digi, *Digi XBee® ZigBee Mesh Kit Product Datasheet*, 2017. https://www.digi.com/pdf/ds-xbee-zigbee-mesh-kit.pdf.

[31] Seeed Studios, "Grove - Light Sensor v1.2." https://seeeddoc.github.io/Grove-Light_Sensor_v1.2/.

[32] Pino-Tech, *Soilwatch 10 User Manual*, January 2018.

[33] Nanyang Senba, *PIR Motion Detector Module*, 2016.

[34] Velleman, *Analog Humidity Sensor Board MM102 User Manual*, August 2016.

[35] Velleman, *VMA447 Mini Peristaltic Pump 6 V User Manual*, April 2019. https://www.velleman.eu/downloads/29/vma447_a4v01.pdf.

# Appendix A

# Equipment List

- Digi XBee ZigBee Mesh Kit
  - (3) Digi XBee ZigBee Modules (SMT)
  - (3) Digi XBee Grove Development Board
- Battery cell cases and batteries
  - (2) 3 x AA
  - (1) 4 x AA
- Grove Light Sensor
- Grove Temperature Sensor (NTC)
- (3) Grove Relay
- Grove Water Atomizer
- Multicore wires
- Wood
  - 300 mm*600 mm*5 mm plywood board
  - (2) 2400 cm*1.8 cm*1.8 cm bars
- Wood glue
- Wood sandpaper
- LED lamp
- Pino-Tech SoilWatch 10
- Plastic cases

- Resistors:
  $1200\,\Omega$
  $2200\,\Omega$
  $3900\,\Omega$
- Soldering iron
- SB612A PIR sensor
- Tubing
- Velleman VMA447 Peristaltic Pump
- Velleman MM102 Humidity Sensor

# Appendix B

# Hardware Datasheets

## B.1 Digi XBee ZigBee (S2D)

Table B.1: Digi XBee ZigBee (S2D) datasheet.

| Parameter | Min | Type | Max | Unit |
|---|---|---|---|---|
| Protocol | - | ZigBee PRO 2007 | - | - |
| Chipset | - | Silicon Labs EM357 | - | - |
| Operating Voltage | - | 5 | - | V |
| Operating Temperature | -40 | - | 85 | $^{o}$C |
| ADC Inputs | - | 4 | - | - |
| ADC Input Voltage | - | 1.2 | - | V |
| Digital I/O | - | 15 | - | - |
| Indoor Range | - | - | 60 | m |
| Outoor Range | - | - | 1200 | m |
| Transmit Current | 33 | - | 45 | mA |
| Transmit Power | 3.1 (+5) | - | 6.3 (+8) | mW (dBm) |
| Receive Current | 28 | - | 31 | mA |
| Receiver Sensivity | -100 | - | -102 | dBm |

*Source:* Digi XBee® ZigBee Mesh Kit Product Datasheet [30]

## B.2 Grove Light Sensor V1.2

Table B.2: Grove Light Sensor V1.2 datasheet.

| Items | Parameter | Min | Type | Max | Unit |
|---|---|---|---|---|---|
| VCC | Operating Voltage | 3 | - | 5 | V |
| I | Operating Current | 0.5 | - | 3 | mA |
| - | Response Time | 20 | - | 30 | ms |
| - | Peak Wavelength | - | 540 | - | nm |

*Source:* Grove - Light Sensor v1.2 [31]

## B.3 Grove Relay

Table B.3: Grove Relay datasheet.

| Items | Parameter | Min | Type | Max | Unit |
|---|---|---|---|---|---|
| VCC | Operating Voltage | 3.3 | - | 5 | V |
| I | Operating Current | - | 100 | - | mA |
| $V_s$ | Switching Voltage | - | 250 (30) | - | VAC (VDC) |
| $I_s$ | Switching Current | - | - | 5 | A |

*Source:* `http://wiki.seeedstudio.com/Grove-Relay/`

## B.4 Grove Temperature Sensor (NTC)

Table B.4: Grove Temperature Sensor (NTC) datasheet.

| Items | Parameter | Min | Type | Max | Unit |
|---|---|---|---|---|---|
| VCC | Operating Voltage | 3.3 | - | 5 | V |
| TR | Temperature Range | -40 | - | 125 | °C |
| - | Accuracy | - | ±1.5% | - | °C |
| ZP | Zero Power Resistance | - | 100 | - | kΩ |
| B | Nominal B Constant | 4250 | - | 4299 | K |

*Source:* Grove Temperature Sensor User Manual V1.0 [29]

## B.5 Pino-Tech SoilWatch 10

Table B.5: Pino-Tech SoilWatch 10 sensor datasheet.

| Parameter | Min | Type | Max | Unit |
|---|---|---|---|---|
| Input Voltage | 2.8 | 5 | 5.5 | V |
| Output Voltage | 0 | - | 3 | V |
| Operating Temperature | 2 | - | 45 | C |
| Current | - | 24 | - | mA |

*Source:* Pino-Tech Soilwatch 10 User Manual [32]

## B.6 SB612A PIR Sensor

Table B.6: SB612A PIR sensor datasheet.

| Parameter | Min | Type | Max | Unit |
|---|---|---|---|---|
| Operating Voltage | 3.8 | - | 15 | V |
| Output Voltage | - | 3.3 | - | V |
| Operating Current | - | - | 30 | $\mu$A |
| Operating Temperature | -20 | - | 55 | $^{o}$C |
| Detection Range | - | - | 8 | m |
| Detection Angle | - | 120 | - | $^{o}$ |
| Delay Range | 2.3 | - | 80 | s |

*Source:* PIR Motion Detector Module [33]

## B.7 Velleman MM102 Humidity Sensor

Table B.7: Velleman MM102 Humidity Sensor datasheet.

| Items | Parameter | Min | Type | Max | Unit |
|---|---|---|---|---|---|
| VCC | Operating Voltage | 2.7 | - | 5.5 | V |
| I | Operating Current | - | 200 | - | $\mu$A |
| - | Accuracy | - | $\pm$3% | - | $^{o}$C |
| - | Response Time | - | 5 | - | s |

*Source:* Velleman Analog Humidity Sensor Board MM102 User Manual [34]

## B.8 Velleman VMA447 Pump

Table B.8: Velleman VMA447 Pump datasheet.

| Items | Parameter | Min | Type | Max | Unit |
|---|---|---|---|---|---|
| VCC | Operating Voltage | - | 6 | - | V |
| F | Flow | - | 39 | - | mL/min |

*Source:* Velleman VMA447 Mini Peristaltic Pump 6 V User Manual [35]

# Appendix C

# Software Requirements

- XCTU
- python3
- tkinter
- sqlite3
- digi.xbee
- matplotlib

# Appendix D

# Management Suite

## Main

Figure D.1: Main menu.

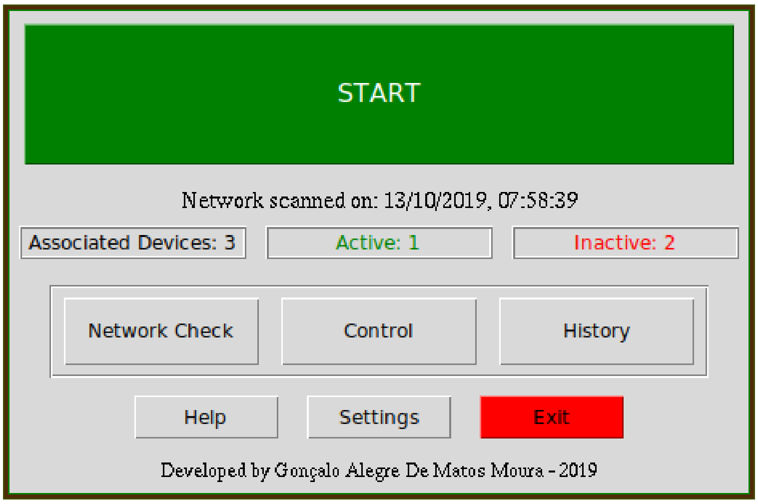
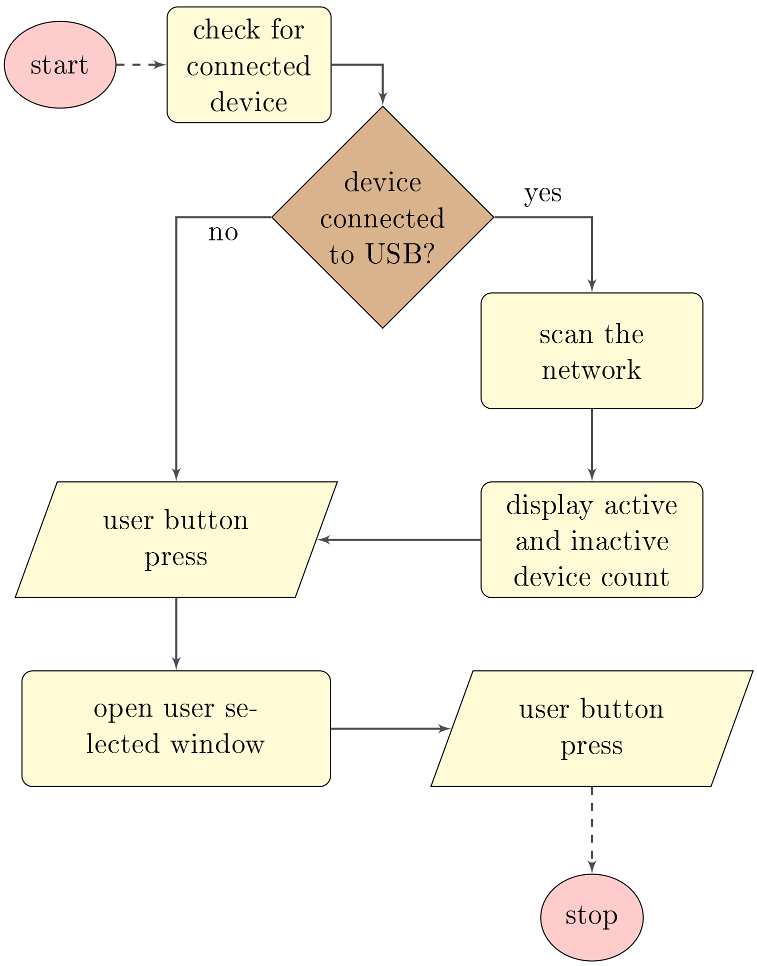


Figure D.2: Main menu flow chart.




## Start

Figure D.3: Start window.

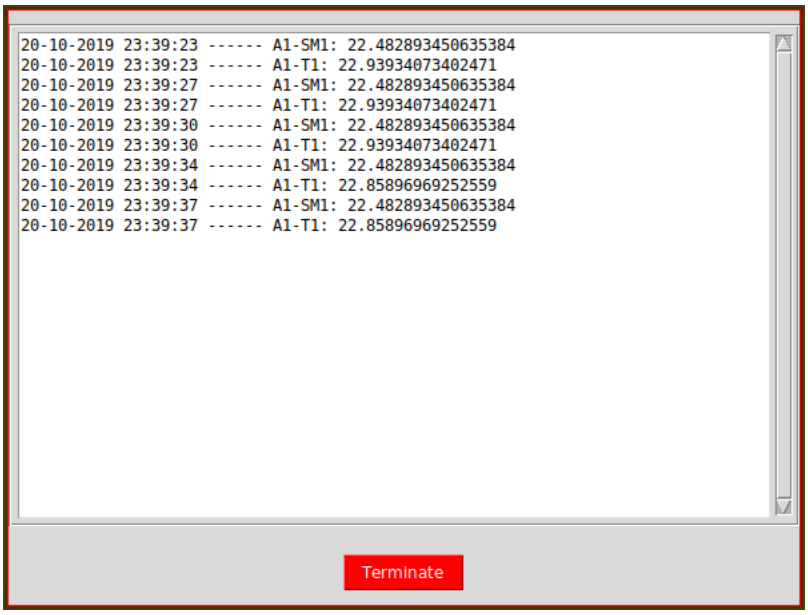
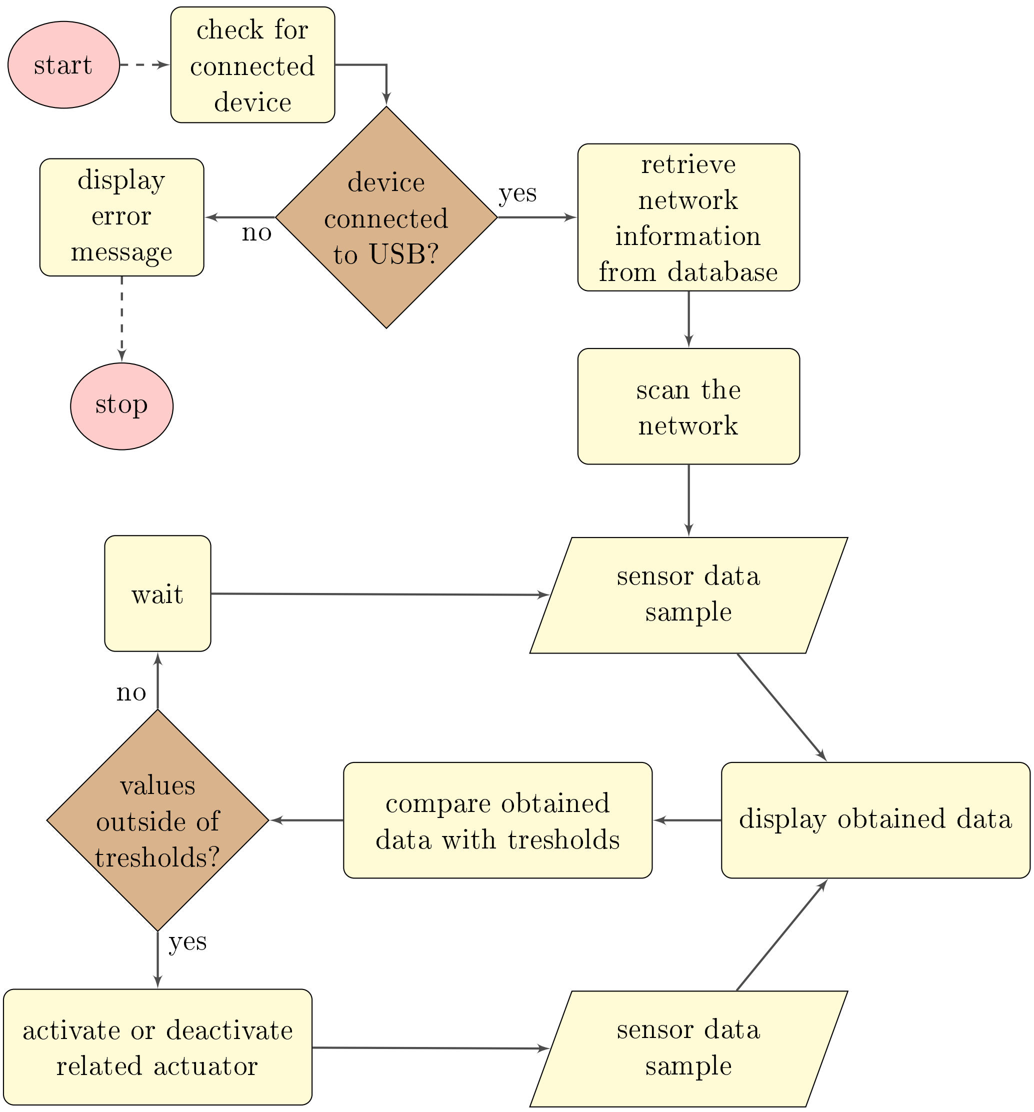


Figure D.4: Start flow chart.



## Network Check

Figure D.5: Network check window, one device connected, two inactive.

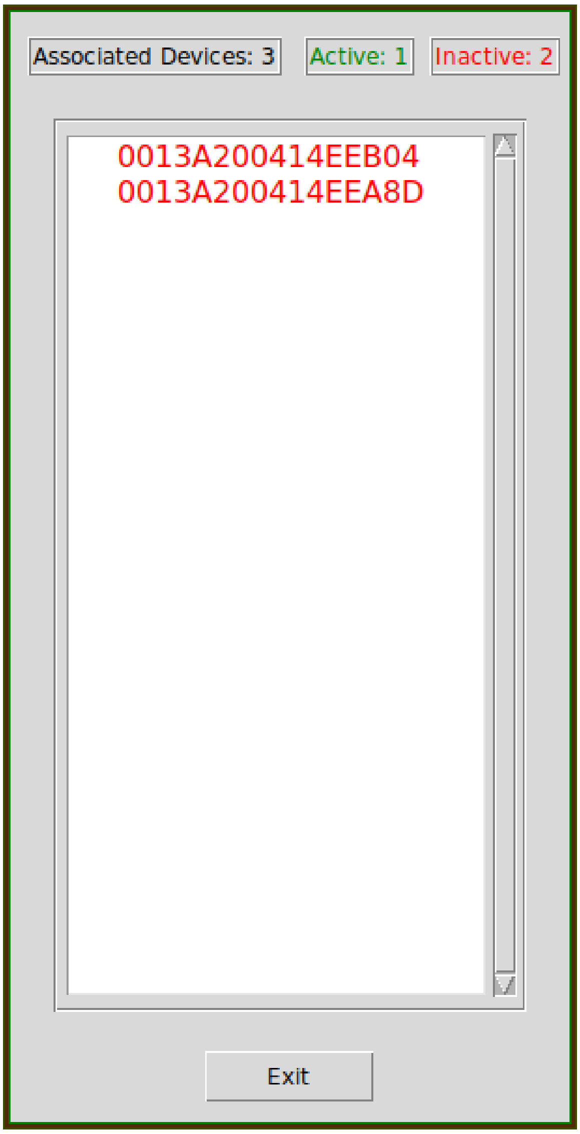
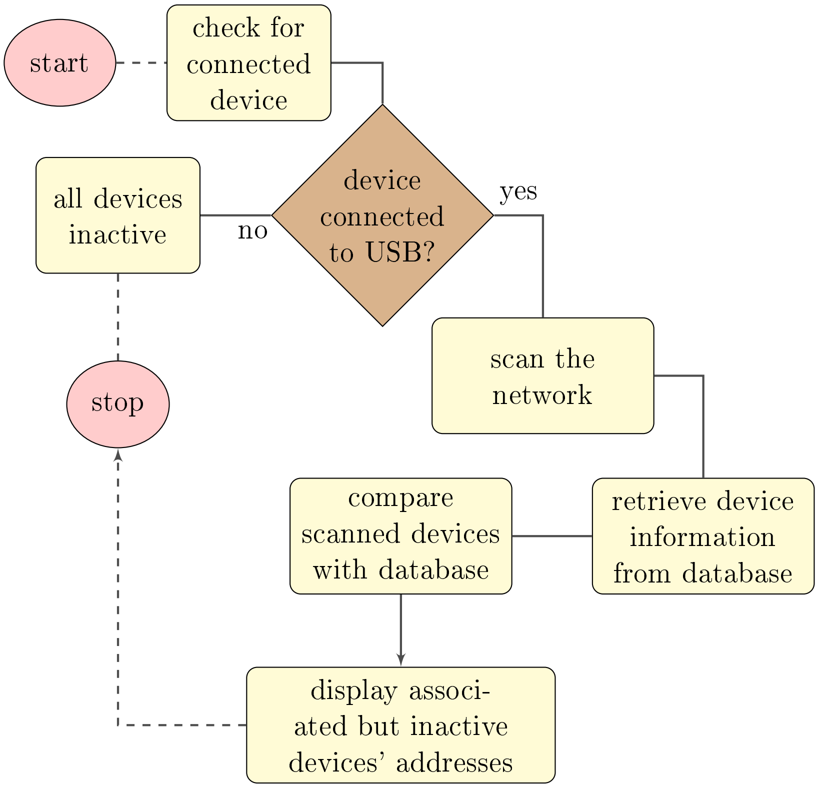


Figure D.6: Network check flow chart.




## Control

Figure D.7: Control window.

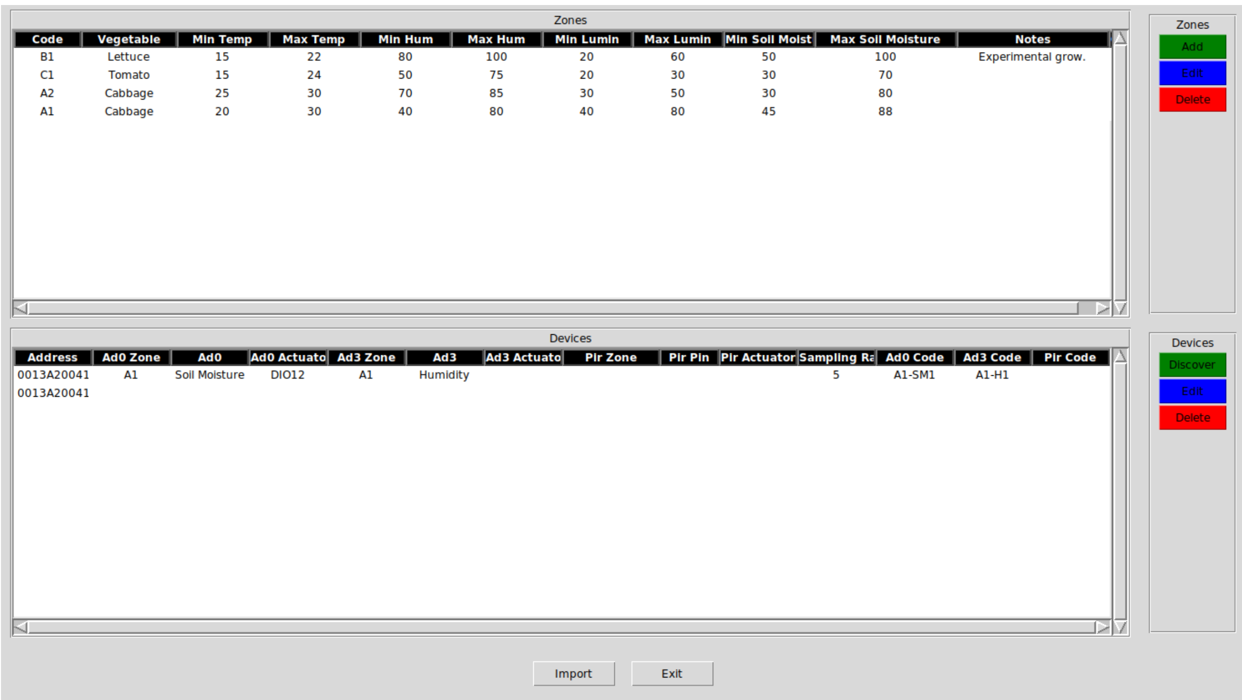


Figure D.8: Control window flow chart.

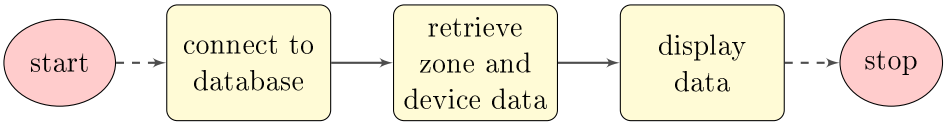
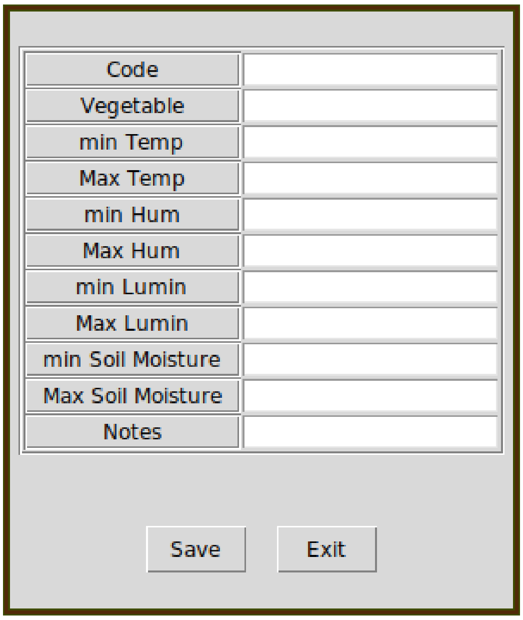
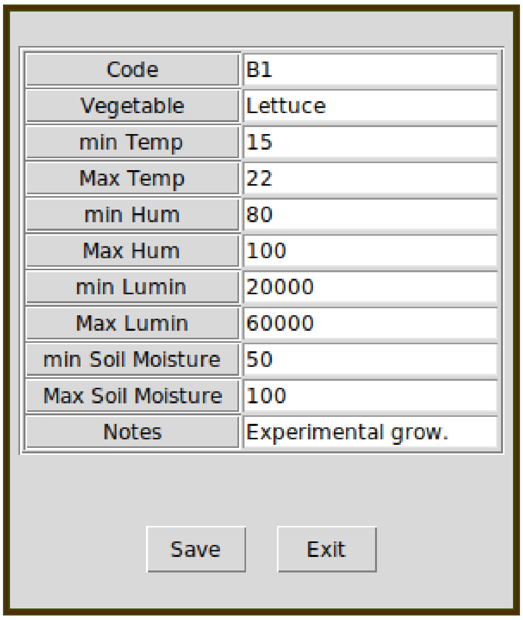



Figure D.9: Zone configuration windows.



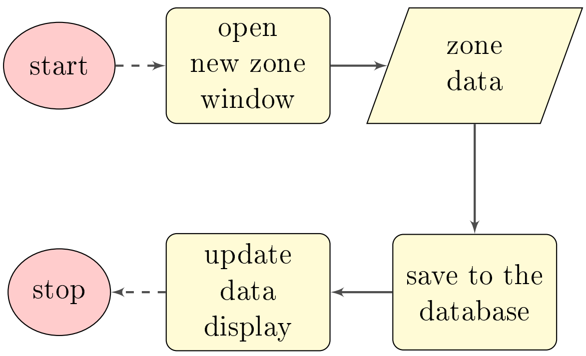

(a) New Zone window.




(b) Zone editing window.

Figure D.10: Control data flow chart.

(a) Add zone flow chart.




(b) Remove zone or device flow chart.

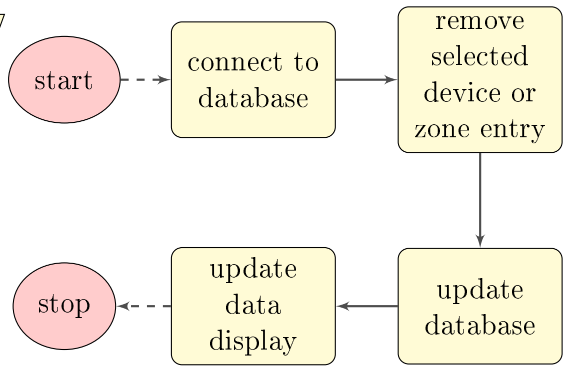
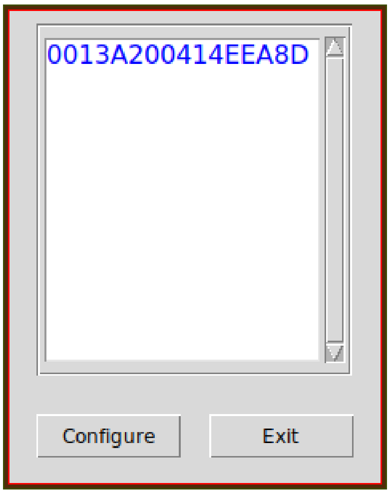


Figure D.11: Device discovery windows.

(a) Device discovery window.




(b) Discovered device configuration window.

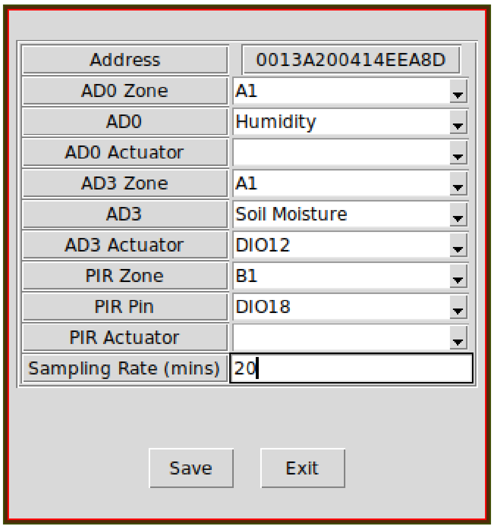



Figure D.12: Device discovery flow chart.

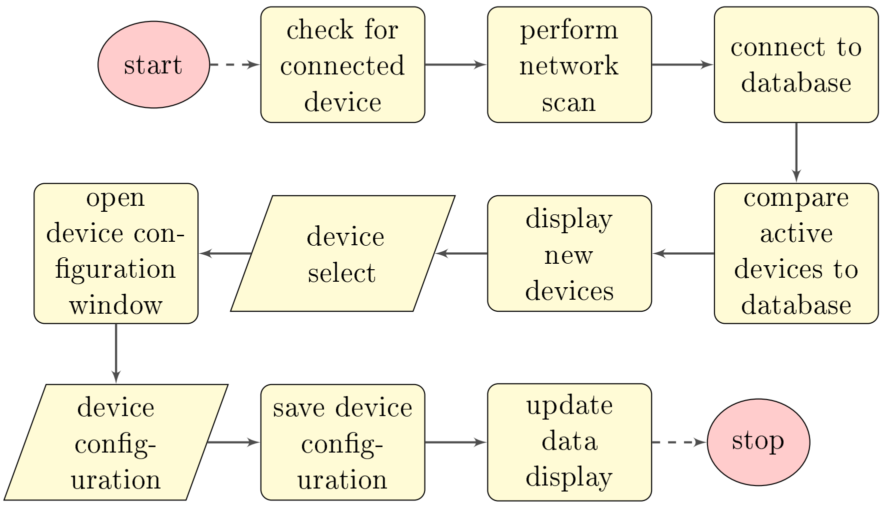
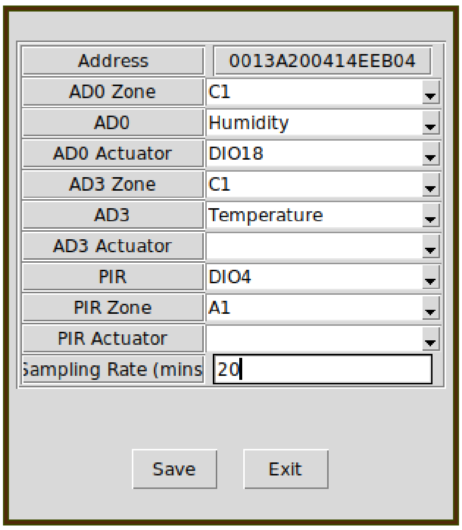



Figure D.13: Device editing window.



## History

Figure D.14: History window flow chart.

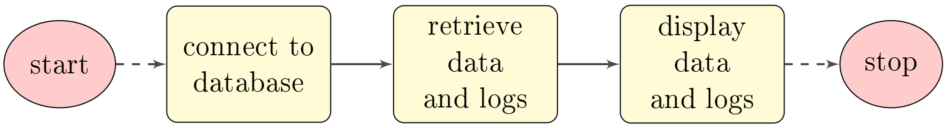



Figure D.15: Sensor selection window.

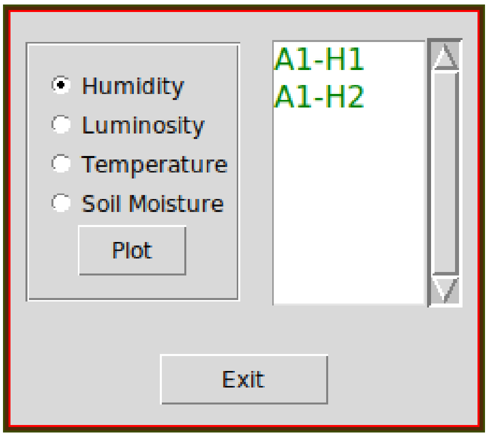



Figure D.16: Visualize window flow chart.

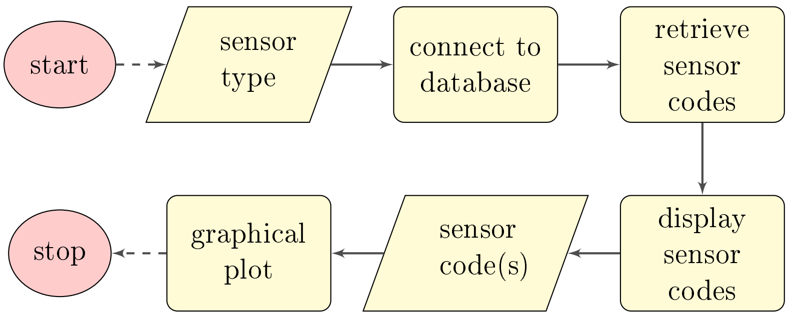
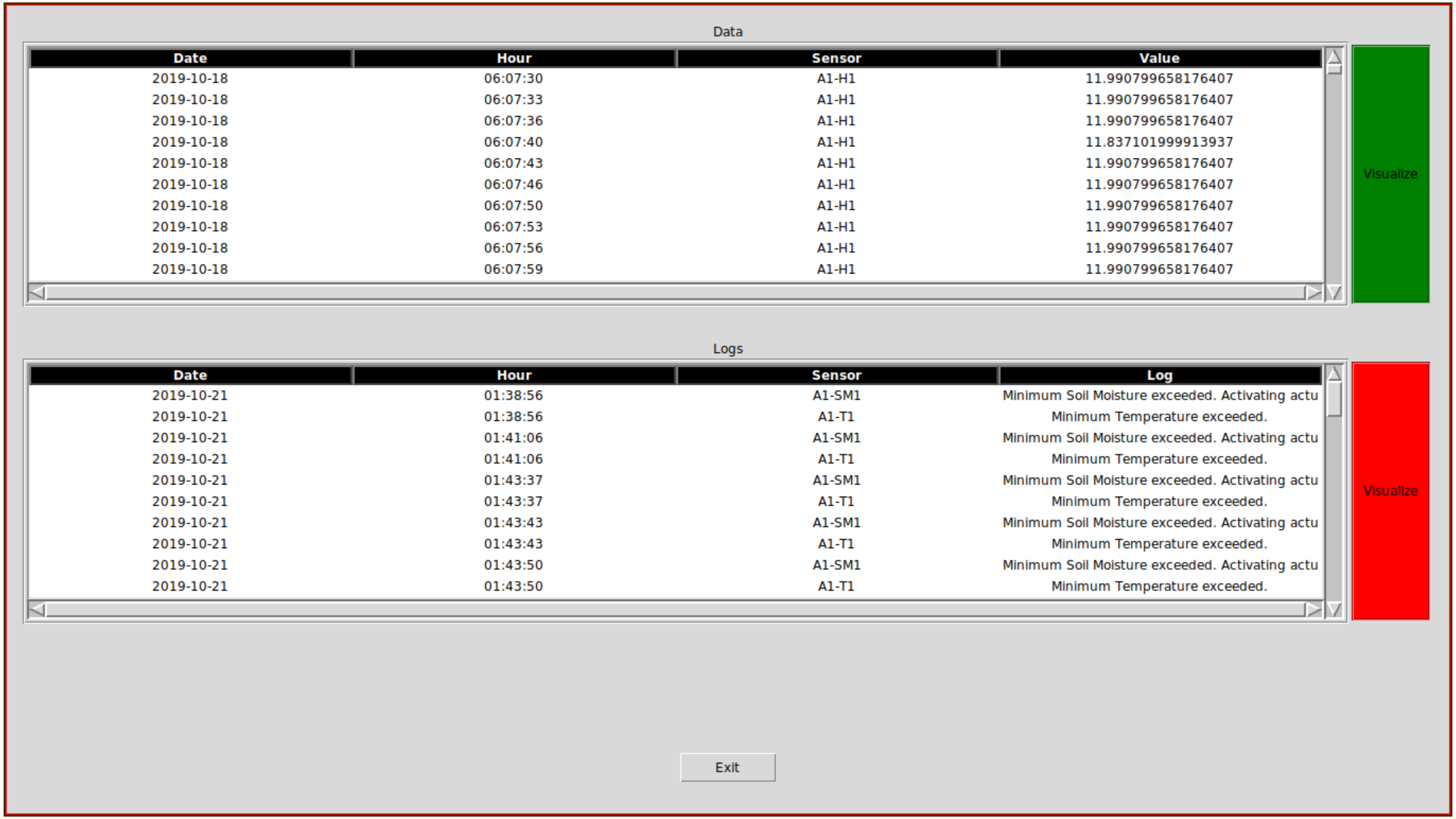


Figure D.17: History window.



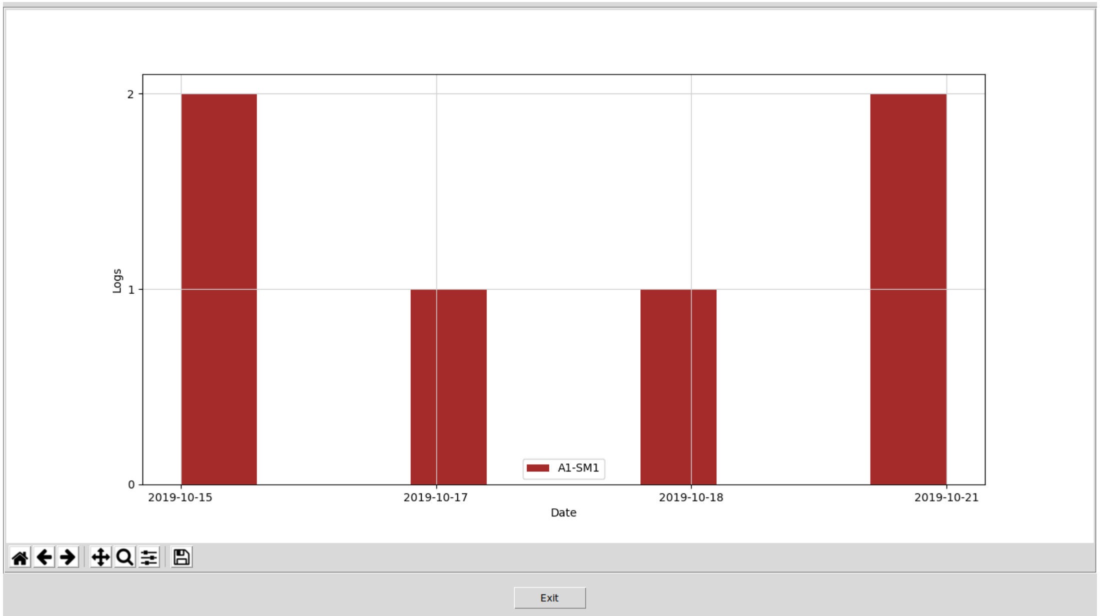
Data

| Date | Hour | Sensor | Value |
|---|---|---|---|
| 2019-10-18 | 06:07:30 | A1-H1 | 11.990799658176407 |
| 2019-10-18 | 06:07:33 | A1-H1 | 11.990799658176407 |
| 2019-10-18 | 06:07:36 | A1-H1 | 11.990799658176407 |
| 2019-10-18 | 06:07:40 | A1-H1 | 11.837101999913937 |
| 2019-10-18 | 06:07:43 | A1-H1 | 11.990799658176407 |
| 2019-10-18 | 06:07:46 | A1-H1 | 11.990799658176407 |
| 2019-10-18 | 06:07:50 | A1-H1 | 11.990799658176407 |
| 2019-10-18 | 06:07:53 | A1-H1 | 11.990799658176407 |
| 2019-10-18 | 06:07:56 | A1-H1 | 11.990799658176407 |
| 2019-10-18 | 06:07:59 | A1-H1 | 11.990799658176407 |

Logs

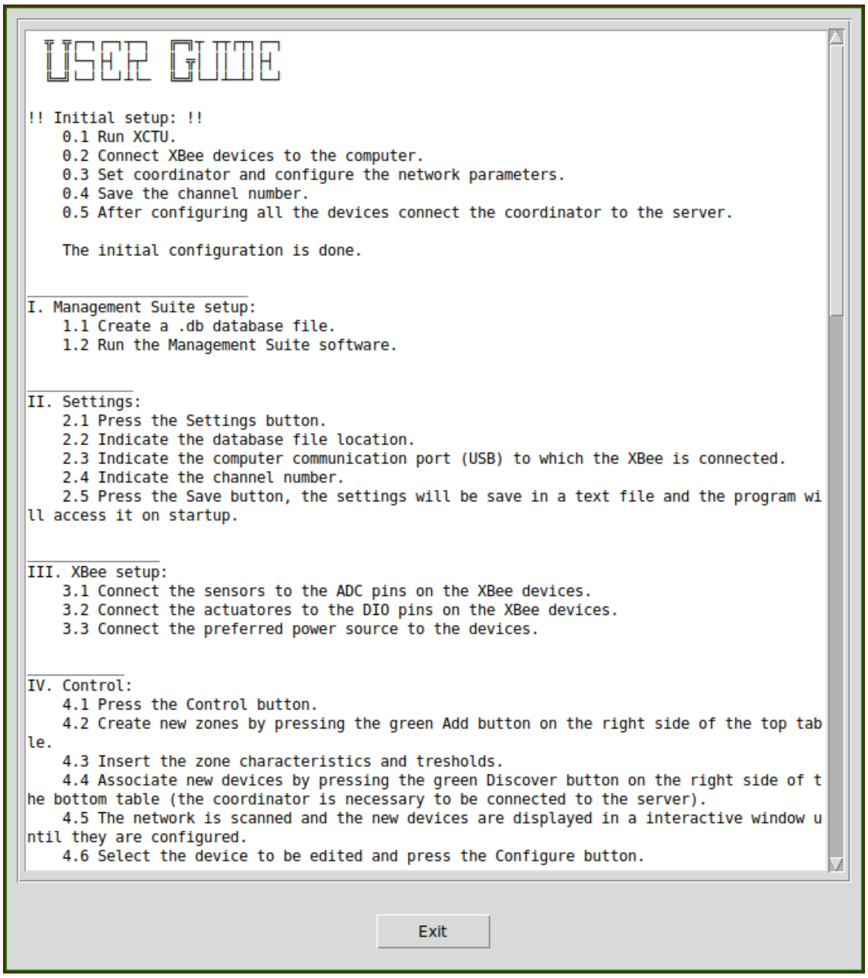
| Date | Hour | Sensor | Log |
|---|---|---|---|
| 2019-10-21 | 01:38:56 | A1-SM1 | Minimum Soil Moisture exceeded. Activating actu |
| 2019-10-21 | 01:38:56 | A1-T1 | Minimum Temperature exceeded. |
| 2019-10-21 | 01:41:06 | A1-SM1 | Minimum Soil Moisture exceeded. Activating actu |
| 2019-10-21 | 01:41:06 | A1-T1 | Minimum Temperature exceeded. |
| 2019-10-21 | 01:43:37 | A1-SM1 | Minimum Soil Moisture exceeded. Activating actu |
| 2019-10-21 | 01:43:37 | A1-T1 | Minimum Temperature exceeded. |
| 2019-10-21 | 01:43:43 | A1-SM1 | Minimum Soil Moisture exceeded. Activating actu |
| 2019-10-21 | 01:43:43 | A1-T1 | Minimum Temperature exceeded. |
| 2019-10-21 | 01:43:50 | A1-SM1 | Minimum Soil Moisture exceeded. Activating actu |
| 2019-10-21 | 01:43:50 | A1-T1 | Minimum Temperature exceeded. |

Figure D.18: Histogram representing sensor logs.



## Help

Figure D.19: Help window displaying the User Guide.



USER GUIDE

!! Initial setup: !!
0.1 Run XCTU.
0.2 Connect XBee devices to the computer.
0.3 Set coordinator and configure the network parameters.
0.4 Save the channel number.
0.5 After configuring all the devices connect the coordinator to the server.

The initial configuration is done.

I. Management Suite setup:
1.1 Create a .db database file.
1.2 Run the Management Suite software.

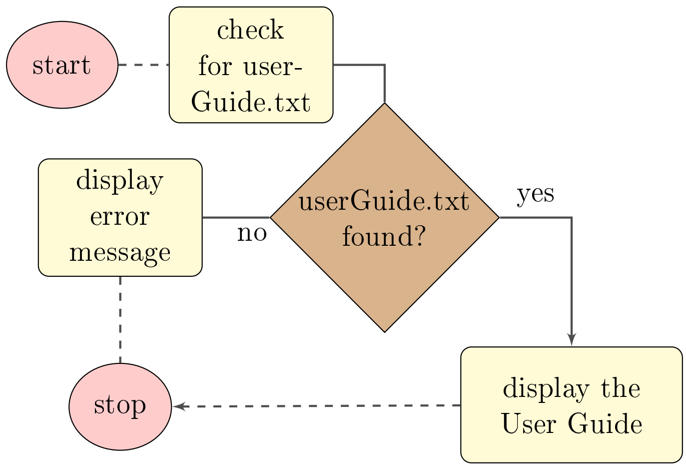
II. Settings:
2.1 Press the Settings button.
2.2 Indicate the database file location.
2.3 Indicate the computer communication port (USB) to which the XBee is connected.
2.4 Indicate the channel number.
2.5 Press the Save button, the settings will be save in a text file and the program will access it on startup.

III. XBee setup:
3.1 Connect the sensors to the ADC pins on the XBee devices.
3.2 Connect the actuatores to the DIO pins on the XBee devices.
3.3 Connect the preferred power source to the devices.

IV. Control:
4.1 Press the Control button.
4.2 Create new zones by pressing the green Add button on the right side of the top table.
4.3 Insert the zone characteristics and tresholds.
4.4 Associate new devices by pressing the green Discover button on the right side of the bottom table (the coordinator is necessary to be connected to the server).
4.5 The network is scanned and the new devices are displayed in a interactive window until they are configured.
4.6 Select the device to be edited and press the Configure button.

Exit

Figure D.20: Help flow chart.




## Settings

Figure D.21: Settings window.

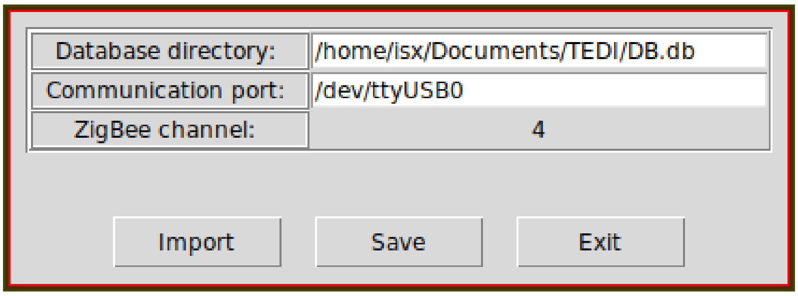



Figure D.22: Settings flow chart.

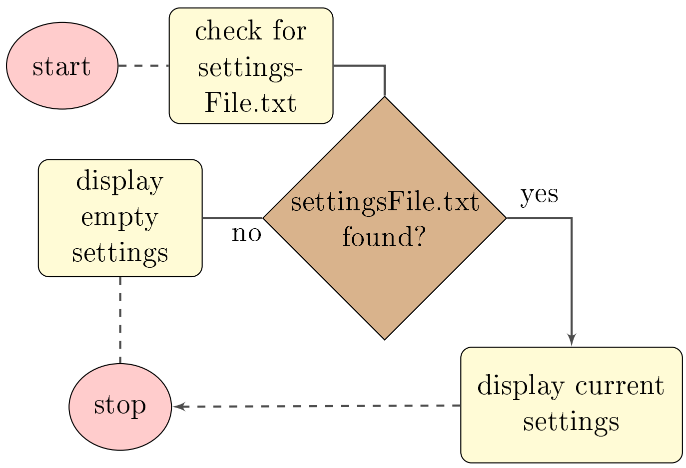
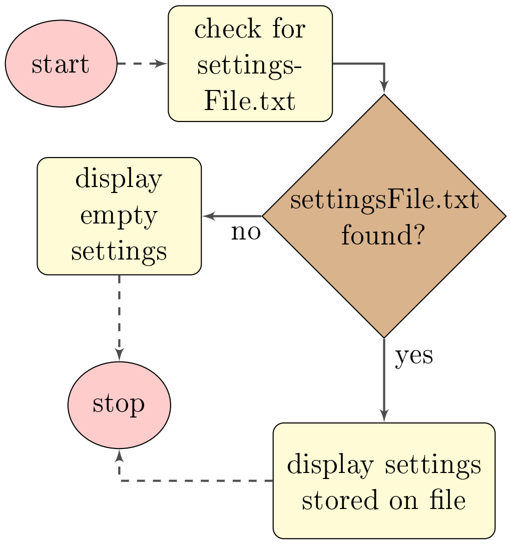
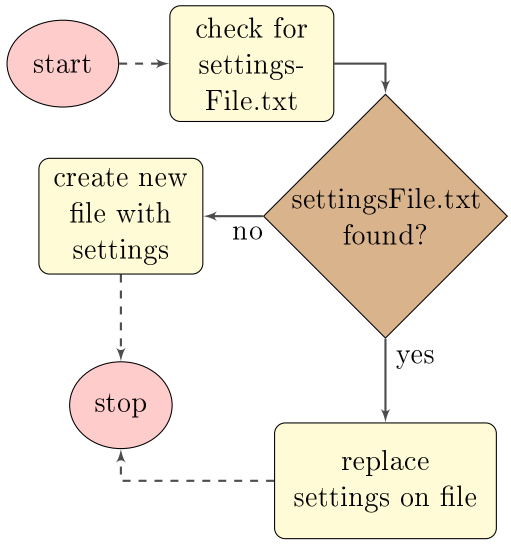


Figure D.23: Settings file flow chart.

(a) Import settings flow chart.




(b) Save settings flow chart.



# Appendix E

# Software Manual

## E.1 XBee Setup

1. Run XCTU.

2. Connect XBee devices to the computer.

3. For the coordinator, set the option Coordenator Enable, **CE**, and configure the network parameters, **PAN ID**.

4. Save the channel number, **CH** and **MY** address.

5. Configure **DH** of devices to 0.

6. Configure **DL** of devices to **MY** address of coordinator.

7. After configuring all the devices connect the coordinator to the server.

The initial configuration is done. Now to finish the setup of the devices, the sensors and actuators must be connected.

1. Connect the sensors to the ADC pins on the XBee devices.

2. Connect the actuators to the DIO pins on the XBee devices.

3. Connect the preferred 5 V power source to the devices.

## Management Suite Setup

1. Create a .db database file.

2. Run the Management Suite software.

### Settings

1. Press the Settings button, a window with empty entry fields like the one represented on Figure D.21 will open.

2. Indicate the database file location.

3. Indicate the computer communication port (USB) to which the XBee is connected.

4. Indicate the channel number.

5. Press the Save button, the settings will be saved in a text file and the program will access it on startup.

### Control

1. Press the Control button, the window shown in Figure D.7 will open.

2. Create new zones by pressing the green Add button on the right side of the top table.

3. Insert the zone characteristics and tresholds.

4. Associate new devices by pressing the green Discover button on the right side of the bottom table (the coordinator is necessary to be connected to the server).

5. The network is scanned and the new devices are displayed in a interactive window until they are configured.

6. Select the device to be edited and press the Configure button.

7. Configure the device parameters.

8. Repeat for the remaining devices.

9. Press the Exit button.

The wireless sensor network is now ready to operate.

## E.2 Frequently Asked Questions (FAQ)

### Activating the wireless sensor network

1. From the main menu press the START button.

2. The wireless sensor network is initialized.

### Terminating the wireless sensor network

1. Press the red Terminate button.

2. The wireless sensor network terminates by setting the actuators to *LOW* and closes the connection with the coordinator.

### View the zone and device listings

1. From the main menu press the Control Button.

   (a) The zone related information is on the top table.

   (b) The device related information is on the bottom table.

2. The rows of the tables can be rearranged according to different parameters by pressing on the column header.

3. Press the Exit button to go back to the main menu.

### Editing zone or device parameters

1. From the main menu press the Control button.

2. Select the desired zone/device parameters from the table.

3. Press the blue Edit button on the right side of the related table.

4. Edit the parameters and press the Save button, the values are written and the window will automatically close.

### Addition of zones or devices

1. From the main menu press the Control button.

   (a) To add new zones press the green Add button on the right side of the top table. Zone codes must be in the form of a letter for the vegetable plus a number that identifies the specific location, such as A1, A2, B1.

   (b) To add new devices press the green Discover button on the right side of the bottom table. Devices must be previously configured in XCTU.

2. Press the Save button.

3. Press the Exit button.

### Removal of zones or devices

1. From the main menu press the Control button.
2. Select the zone/ device to remove.
3. Press the red Delete button on the right side of the related table.
4. Press the Exit button.

### Editing software configuration

1. From the main menu press the Settings button.
   (a) Edit the existing configuration.
   (b) It's also possible to import a configuration file by pressing the Import button.
2. Press the Save button.
3. Press the Exit button.

### Check for inactive devices

1. From the main menu press the Network Check button.
2. If the coordinator is connected, the network is scanned. Inactive devices are identified by their address number which is written on the XBee itself.
3. Press the Exit button.

### Statistical analysis of the network performance

1. From the main menu press the History button.
   (a) The values obtained from the sensors are on the top table.
   (b) The logs registered by the devices are on the bottom table.
2. Press the Visualize button.
3. Select the control parameter to visualize, a text box with the related sensors is displayed.
4. Select the sensor or sensors to be ploted and press the Plot button.
5. The graphical plot is shown.
6. From the plot window is possible to zoom in or out, pan, edit the axis and take a screen capture of the graphical plot.

# Appendix F

# Constructing the Growhouse

Figure F.1: Materials required.

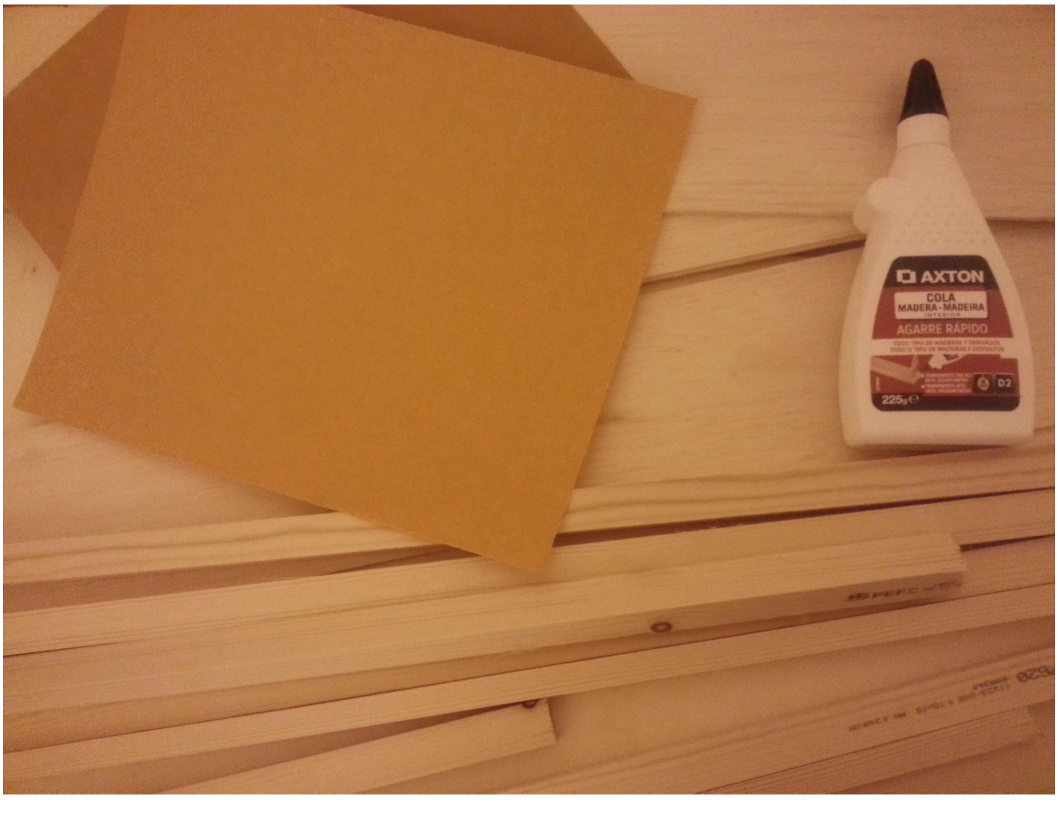


Figure F.2: Structure of the growhouse.

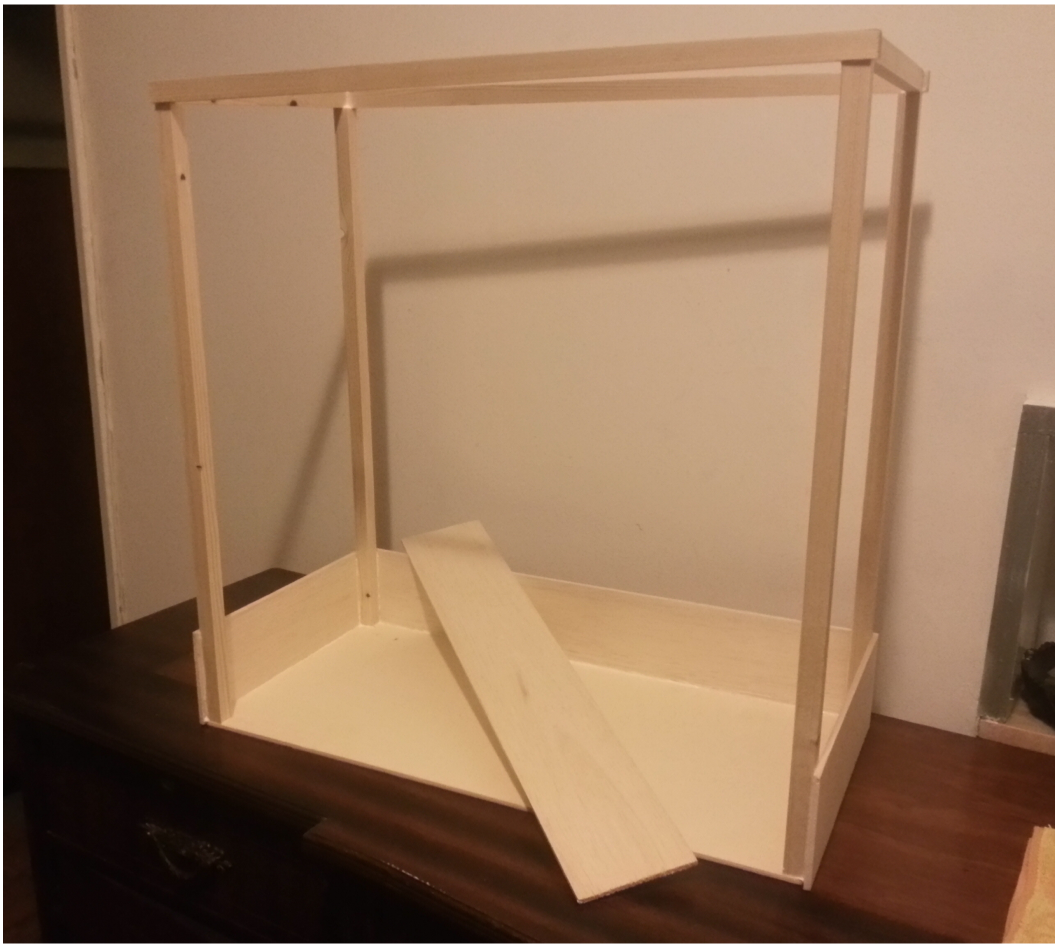


Figure F.3: Growhouse with components installed.

Figure F.4: Growhouse with components installed inside view.